TECHNICAL PAPER No. 4

Scale Model Igloo Magazine Explosion Tests

Naval Proving Ground, Arco, Idaho

August 1946

Army-Navy Explosives Safety Board, 2045 Temporary Building No. 2
Washington, D. C.

TECHNICAL PAPER No. 4

Scale Model Igloo Magazine Explosion Tests

Naval Proving Ground, Arco, Idaho

August 1946

Army-Navy Explosives Safety Board, 2045 Temporary Building No. 2
Washington, D. C.

This report, prepared by Commander R. L. Mann, Bureau of Yards and Docks, U. S. N., while on duty with the Army-Navy Explosives Safety Board, reviews, summarizes, and interprets the available data pertaining to the use of model igloos for predicting the results to be expected from explosions in full-scale tests of Army and Navy earth-covered reinforced concrete igloos.

Commander Mann supervised the field work for recording the data obtained from many of the tests described herein.

In drawing conclusions from these data, the statistical limitation imposed by the many variables are recognized, but the publication of this report is authorized as it represents a distinct contribution to the development of safe standards for the storage of military explosives and ammunition.

12 June 1947
Washington, D. C.

F. H. MILES, Jr.
Colonel, Ordnance Department,
President, Army-Navy
Explosives Safety Board

Scale-model tests of detonations of high-explosive charges in earth-covered igloo magazines and in open storage were held as a sequel to similar tests by the Woods Hole Oceanographic Institution in order to study further the effects of such explosions on next-in-line igloos, to investigate whether the model law holds good in determining various phenomena from explosions, and to determine how increased earth cover on the exploded magazine affects these phenomena. The linear scale factor was 1/10 and the ratio of charge weights was 1/1000. The tests were held in July and August 1946, at the Naval Proving Ground, Arco, Idaho. Eight tests were held, six with 250-pound charges and two with 500-pound charges, simulating certain phases of the 1945 and 1946 full-scale test programs.

The major conclusions were that the model law holds good for air blast, crater diameters, horizontal earth movement, and damage to structures caused by air blast; that it does not hold good for crater depths, vertical ground movement, vertical component of ground shock, or damage to target igloos (which is partly caused by ground shock); that increased earth cover reduces air blast and damage to target structures; that the use of standard service earth-covered igloos does not warrant halving the distance specified by the American Table of Distances for safety of inhabited buildings from unbarricaded charges; and that standard Army revetments around open charges do not reduce air blast generated by detonation of their contents.

CONTENTS

	Page
PART I. INTRODUCTION	1
II. OBJECTS OF THE TESTS	4
III. TEST PROCEDURE.	
1. Test site and conditions	4
2. Order of tests and field lay-out	5
3. Description of model igloos	10
4. Installation of igloos	10
5. Earth cover on igloos	10
6. Primary charges	12
7. Secondary charges	14
8. Window glass tests	14
9. Instrumentation and observations	14
IV. RESULTS.	
1. Test No. 1, fired at 1100, 30 July 1946	19
2. Test No. 1-A, fired at 0835, 10 August 1946	25
3. Test No. 2, fired at 1000, 1 August 1946	35
4. Test No. 3, fired at 1020, 2 August 1946	37
5. Test No. 4, fired at 1030, 5 August 1946	52
6. Test No. 5, fired at 1530, 5 August 1946	56
7. Test No. 6, fired at 1015, 8 August 1946	64
8. Test No. 7, fired at 1500, 8 August 1946	73
V. DISCUSSION.	
1. Appearance of explosions	84
2. Air blast	84
3. Glass breakage	94
4. Fragmentation	97
5. Cratering	98
6. Ground displacement	103
7. Displacement of target igloos	105
8. Damage to target igloos	107
9. Disturbance of contents of target igloos	108
VI. CONCLUSIONS.	
1. Validity of model tests	109
2. Effect of increased earth cover	109
3. Value of revetments	110
VII. REFERENCES	110
APPENDIX A. FIELD DATA	111
APPENDIX B. CALIBRATION OF BLAST METERS AND GAGES	128

A model igloo explosion.

PART I. INTRODUCTION

In making full-scale tests at the Naval Proving Ground, Arco, Idaho, to investigate the safety and feasibility of spacing igloo magazines at half the normal standard distance in order nearly to double the capacity of ammunition storage depots, the Army-Navy Explosives Safety Board found not only that explosions would not propagate from one igloo magazine to another at the halved distance, but that damage to adjacent igloos was slight.

In order further to investigate the effects of explosions in igloos on their neighbors without going to great expense, the Board arranged for tests to be held using one-tenth linear scale models of the standard Army and Navy 27- by 80-foot igloo magazine. These tests were begun in October 1945 by the Underwater Explosives Research Laboratory, Woods Hole, Mass., in a field at Camp Edwards, Mass. For a report on these tests, see reference 4, part VII.

The model law for explosions states that for equal peak blast pressures, the ratio of the cube root of the charge weight to the distance from the charge weight is constant, or

$$\frac{(W_1)^{1/3}}{d_1}=\text{Constant}=\frac{(W_2)^{1/3}}{d_2}$$

where W_1 and W_2 are charge weights, and d_1 and d_2 the distances, respectively, between those charge weights and points of equal blast pressure. In the full-scale tests, the charge weight was 250,000 pounds (net weight of high explosive). Hence in order to determine the correct charge weight for the one-tenth scale model system, $W_2=250{,}000$ pounds and $d_2=10d_1$ are substituted in the above equation, giving

$$\frac{(W_1)^{1/3}}{d_1}=\frac{(250{,}000)^{1/3}}{10d_1}$$

$$W_1=\frac{250{,}000}{1{,}000}=250 \text{ pounds}$$

similarly, the correct charge weight in a 1/10th-scale model system representing a 500,000-pound explosion is 500 pounds. These relationships agree with the law that similar volumes, hence similar masses of equal density, are to each other as corresponding linear dimensions cubed.

In the first model test, which reproduced the first Arco test, four igloos were set up representing a section of an ammunition depot with halved spacing, and a 250-pound charge was placed in one while the others served as "targets." The blast pressures scaled very satisfactorily, the values as measured by piezo-electric gages falling within 10 percent of those obtained at Arco.

The damage done to the next-in-line target igloo was more serious than that experienced at Arco, especially in that the arch sustained longitudinal cracks and was lifted bodily from the floor slab, while the latter was displaced away from the explosion approximately 1 inch. It appeared that ground shock was the primary cause of the damage, and was relatively more severe than in the full-scale test. No appreciable damage was suffered by the other target igloos.

The crater was relatively much deeper in the model test. This seems to correspond to the occurrence of greater ground shock.

Complete data on fragment distribution was not obtained; hence, it was not possible to draw a comparison with the missile map prepared from the first Arco test. However, very few large pieces of concrete were thrown any distance, most of the igloo being pulverized, and no fragment damage to the target igloos occurred. This was in agreement with the Arco test.

The main discrepancies between the model and prototype tests, i. e., the more severe damage to a target igloo and the greater earth displacement in the case of the model test, were ascribed to three possible causes:

(*a*) The difference in soils of the two sites, that at Arco consisting of silt topsoil over beds of

sand and gravel, underlaid by multiple strata of lava and volcanic ash to a great depth (which has been shown to be a poor medium for transmitting shock waves to large distances), while the soil at Camp Edwards was of sand-clay-loam underlain by clay, sand, and rock strata. The latter soil may have had a greater shock-transmission capability which would have contributed to the increased earth shock and more severe damage experienced in the model test.

(*b*) The failure to scale properly the force of gravity in the model system. To fully meet the requirements of the model laws in order to reproduce the damage phenomena of the full-scale test, either the force of gravity or the density of all matter in the model system should have been multiplied by the scale factor, 10. Theoretically, it would be possible to increase gravity by revolving all components in a large centrifuge during the test, or to scale up the densities by using special heavy soil, concrete, and steel. Since such measures were impracticable, this defect in the model tests is regarded as inherent and some influence on the results is expected.

(*c*) Difference in foundation construction. In the prototype igloo the base of the arch barrel is keyed and dowelled to a continuous spread footing wall, whereas, in constructing the model the arch barrel was set on the base slab about 2 hours after the latter was cast, and a mortar fillet or rim trowelled on around all sides between the lower outside surface of the barrel and the projecting edge of the base slab. Reinforcing steel projecting from the lower edge of the barrel penetrated the base slab, thus dowelling the two sections together. Poor bonding of the concrete surfaces, and of the dowel steel in the concrete of the base which had reached initial set before the steel was inserted, may account for the complete separation of the arch from the base in the Camp Edwards test. Perfect bonding of the arch to the base would have given the arch fixed ends and thus greater relative strength than the prototype arch, which is regarded as a two-hinged arch, a structure of less load-bearing capacity than a fixed arch of the same section.

The second model test repeated Test No. 1 with the addition of a reinforced concrete pier running lengthwise under the slab directly beneath each lower edge of the arch, to simulate the footing walls of the prototype. The two piers rested on a thin layer of sand over the subgrade, and the space between the base slab and the upper surface of the sand layer was filled with tamped borrowed earth. This construction would be expected to diminish somewhat the intensity of earth shock transmitted upward into the structure because of the relative looseness of the fill as compared with undisturbed soil. However, the possibility of weak bond between the parts of the structure was not changed.

In this test the arch barrel and the front end wall were separated from the base and suffered longitudinal cracks. The two piers were cracked in the middle. This damage reproduced that of the first test quite closely.

The piers did not materially affect the results. Blast pressures and other phenomena agreed closely with those of Test No. 1.

In Model Test No. 3, the arrangement of components was the same as before but the charge was in the open rather than within an igloo. This did not simulate any Arco test, but served to furnish a basis of comparison with detonations within igloos as in Test No. 1, and with detonations of charges uncovered but surrounded by earth revetments as in Test No. 5.

The near side of the next-in-line target igloo sustained considerable damage involving diagonal and longitudinal cracking and an inward deflection of ⅞ inch in test No. 3. The front end wall was badly cracked and separated from the arch. The rear wall was separated at the base. Obviously, air blast had a hand in causing this damage. When the shot was repeated in Test No. 4, using the damaged igloo as target, the damage was increased. Peak air blast pressures recorded by instruments were greater than in Tests No. 1 and No. 2. These tests clearly demonstrated the effectiveness of the earth-covered igloo in minimizing damage by air blast to nearby structures when explosives within the igloo are detonated.

It had been thought that a revetment surrounding an open charge would provide little protection to targets, other than through stoppage of flat-trajectory missiles. Since in Test No. 3 considerable damage was inflicted on the target igloo, it appeared either that the test had failed to scale from a similar Arco test wherein a revetment was present and no damage was done to the target igloo, or that a revetment is in fact of value in reducing blast effects on neighboring structures, contrary to the prevailing opinion.

Test No. 5, which repeated the second test with the addition of a revetment around the charge should have clarified this question. In this case

the blast did not damage the target igloo as severely as in the previous test, which normally would lead to the conclusion that revetments are of definite value in protecting nearby structures from blast. However, by the time this test was held, winter had set in at Camp Edwards and the ground was frozen, thus injecting doubt as to the degree of protection afforded by the frozen cover on the target igloo, which otherwise might have sustained the same damage as in Test No. 3. The results were therefore regarded as inconclusive.

Summarizing, some of the conclusions from the first five model tests were:

(*a*) The model laws hold good for peak air blast pressures, and for transient displacements of target igloos due to air blast.

(*b*) Results of model igloo tests are reasonably reproducible.

(*c*) Air blast and damage consequent thereto is materially reduced when stacks of high explosives are stored in earth-covered igloos instead of in the open.

(*d*) When the contents of an earth-covered igloo are detonated, the major cause of damage to a target earth-covered igloo appeared to be earth shock, while air blast was responsible for minor cracking of the arch.

Left in some doubt were the following questions:

(*a*) Whether the difference in degree of damage suffered by the target igloo in the full scale Arco test and that suffered by the model target igloo was due to the failure properly to scale the acceleration of gravity, to soil differences of the two sites, or to differences in igloo construction.

(*b*) To what extent target structures are protected from blast by an earth revetment surrounding the charge.

Further tests at Camp Edwards were deferred and the Board subsequently decided to transfer the remaining model igloos to Arco, Idaho, with a view to continuing the program there in the spring or summer of 1946.

Shifting the scene of the tests to Arco had the great advantage of resolving one of the factors of confusion, i. e., the difference in soils. To this end, the first Arco model test was to reproduce precisely the No. 1 Camp Edwards test, anticipating that the critical question of the applicability of the tests to damage determination might be answered thereby, and that valuable information on the effect of variation in soils on damage to target igloos might be obtained.

While the 1946 program was in the early planning stage, Capt. E. R. Gayler (CEC) USN (Ret.), member of the Board, propounded that whereas the full-scale Arco test of 1945 had shown that the distance heretofore considered safe for inhabited buildings from 250,000 pounds of high explosives in a standard igloo is not adequate for the protection of occupants of the building, it is possible that by heavily increasing the earth covering on standard magazines the present safety distances may be maintained with safety to the occupants of the buildings without excessive expense. Accordingly, it was decided to include in the 1946 model program a series of tests with progressively increasing earth cover, in order to indicate the general effects of such increase, and for purpose of later comparison with the results of a full-scale test with an extra heavy cover.

Also included was a series of tests of window glass simulating the tests of windows in barracks buildings in the 1945 and 1946 full-scale programs. It was not expected that the incidence of window breakage in the model tests would truly reproduce that experienced in the large tests, since the glass was to be mounted in free-standing panels rather than in walls of enclosed buildings, and, moreover, it was recognized that peak blast pressure is not a precise criterion for rupture of sheet glass, particularly in the larger sizes where the effect of impulse is felt. However, it was thought that the breakage might be roughly comparable, that it would illustrate the effect of augmented earth cover, and that the additional information on the effect of pane size and orientation which could be obtained would prove of value.

No effort was to be made to determine the probability of sympathetic detonation between charges within adjacent igloos or revetments by means of the model tests, as it is not considered that the occurrence or nonoccurrence of this phenomenon in a model system has any bearing on its occurrence in the prototype system, owing to the failure of the force of gravity to scale and to uncertainties such as whether a bomb might fall off the top of the stack and initiate a detonation in the large magazine, whereas even if it should chance to fall in the same manner in a model igloo, the height of fall might nevertheless not be sufficient to cause detonation.

PART II. OBJECTS OF THE TESTS

1. To determine the effect of the difference in soils of Camp Edwards, Mass., and Arco, Idaho, on cratering, earth shock, and damage to target igloos, in order to discover whether the failure of these phenomena to follow the model law at Camp Edwards was due to the dissimilarity in soils or to inherent invalidity of scaling.

2. To ascertain the effect on air blast, cratering, earth shock, and damage to target structures, when the earth cover on the exploded igloo is made thicker.

3. To find whether an earth revetment surrounding a detonated open charge is of value in protecting nearby structures from blast.

4. To obtain data for study in conjunction with results of full-scale tests to be held at a later date.

PART III. TEST PROCEDURE

1. Test Site and Conditions

The Naval Proving Ground extends northward from a point on highway U. S. 20 approximately 40 miles northwest of the town of Blackfoot, Idaho, and 22 miles southeast of Arco, Idaho. It is situated on the western portion of the Snake River Plain, a vast expanse of desert bordering the valley of the Snake River. To the north and west of the firing range lie the lofty and rugged Lemhi, Lost River, and Sawtooth Mountains, and their interjacent valleys of the Little and Big Lost Rivers, which follow southeasterly courses into the plain and disappear in sinks. To the east and south lie a number of large and small buttes, the largest of which, Big Southern Butte, rises 2,350 feet above the plain. The region is semiarid, with a mean annual rainfall of 12.5 inches; the vegetation consists of sagebrush, bunchgrass, a dwarf cactus, and similar growths. The plain was formed by intense volcanic activity in the Pliocene period, when the prehistoric valley of the Snake was repeatedly flooded with lava; and eruptions continued at a decreasing rate until recent times, the latest flows, which occurred at Craters of the Moon National Monument 40 miles to the southwest, having occurred only a few hundred years ago. The desert is covered with a multitude of low cones, vents, and lava outcrops. On the test site, which is relatively level, the complex basaltic layers are covered with alluvium consisting of gravel beds and silt to an average depth of perhaps 20 feet. The surface material is probably aeolian. The approximate position of the test site is 43°36′ north latitude, 112°53′ west longitude; the elevation is about 4,800 feet. During the tests, meteorological conditions averaged approximately as follows: Temperature 90° F; Humidity 20 percent; Barometer 26.1″ hg. The days were generally clear or partly cloudy, with still air in

Figure 1. View of test site from firing station.

the mornings and southwest winds increasing to as much as 20 m. p. h. in the late afternoons.

2. Order of Tests and Field Lay-out

The individual test sites were separated from each other by about 1,500 feet. Figures 1, 2, and 3 are photographs of the general scene and of the set-up for the first test. The shots were numbered 1 to 7. The first five each used two model igloos; one a "primary" igloo in which the charge was detonated, and the other a "target" igloo the damage to which was observed. The arrangement on the ground for these five tests is illustrated by figures 4, 5, and 6. In shots 6 and 7, uncovered charges were detonated against target igloos, the charge being surrounded by an earth revetment, constructed to scale after the standard Army open storage revetment in Shot 6, and laid in the open ground in Shot 7. These arrangements are shown in figure 7. Tests of window glass were included in Shots 1 through 7; the set-up for these is illustrated by figure 11. An eighth shot was added to the program in the field; this repeated Shot 1 and was numbered 1–A.

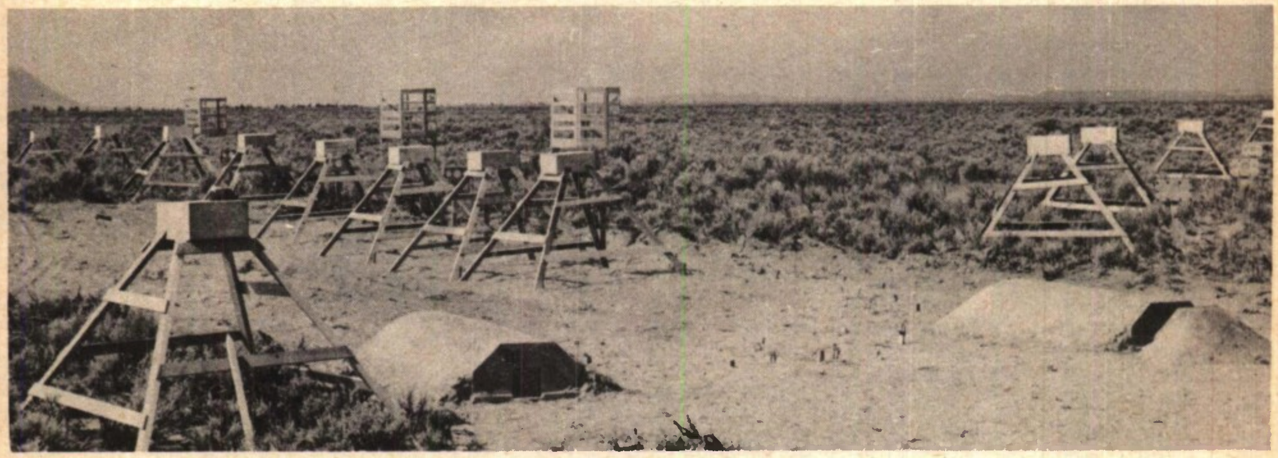
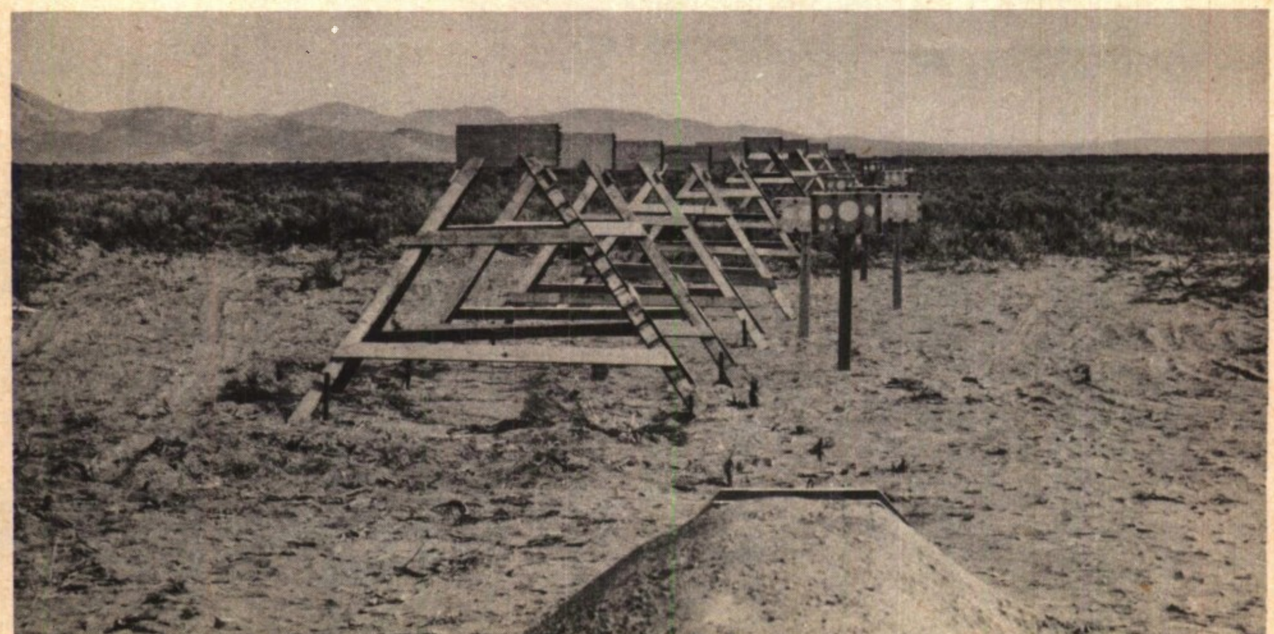


Figure 2. General view of set-up for Test 1, looking southwest.

Figure 3. Looking north along meter line No. 1 from behind primary igloo Test 1.



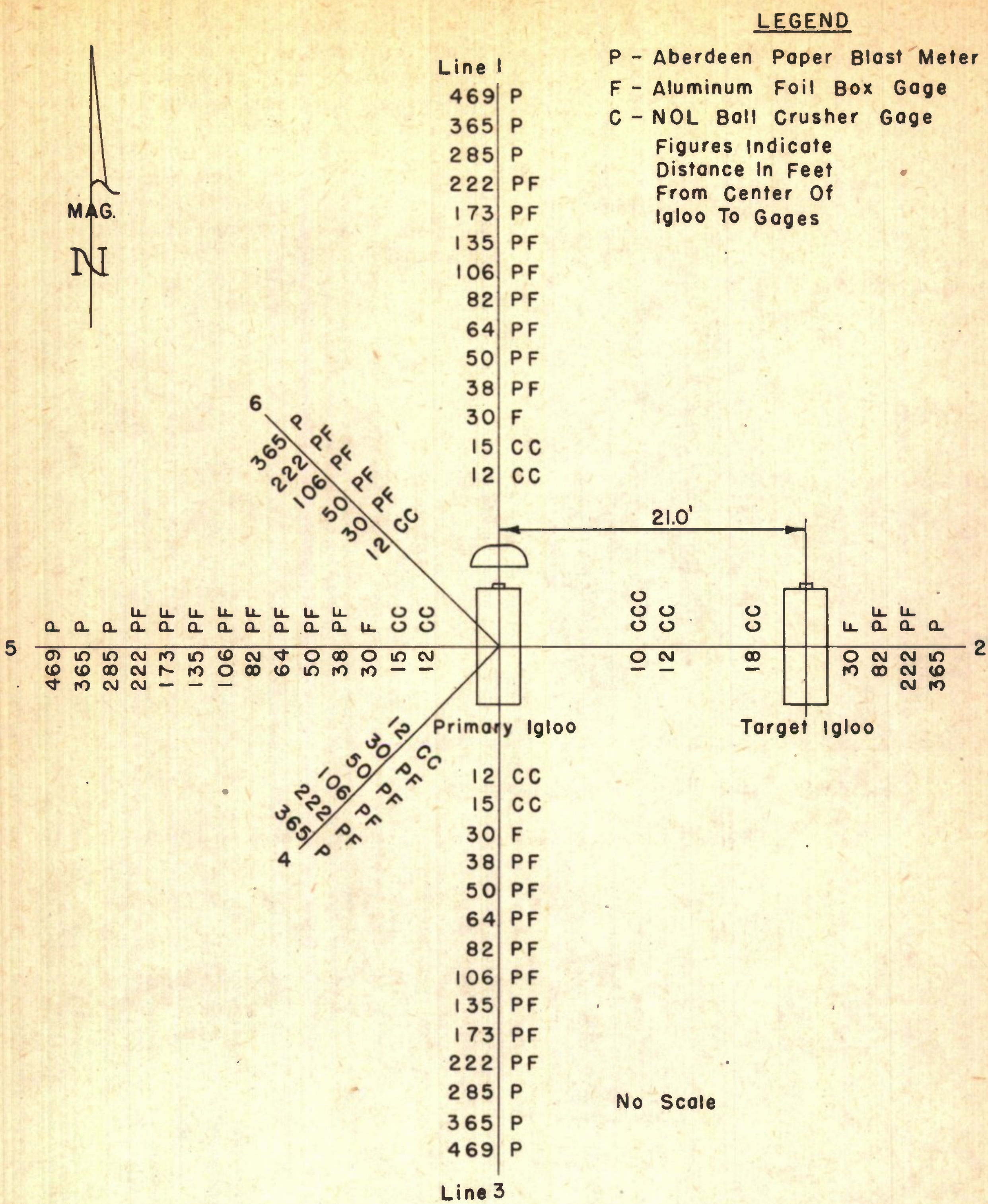


FIG. 4

FIELD LAYOUT &
INSTRUMENT ARRANGEMENT

Test No. 1

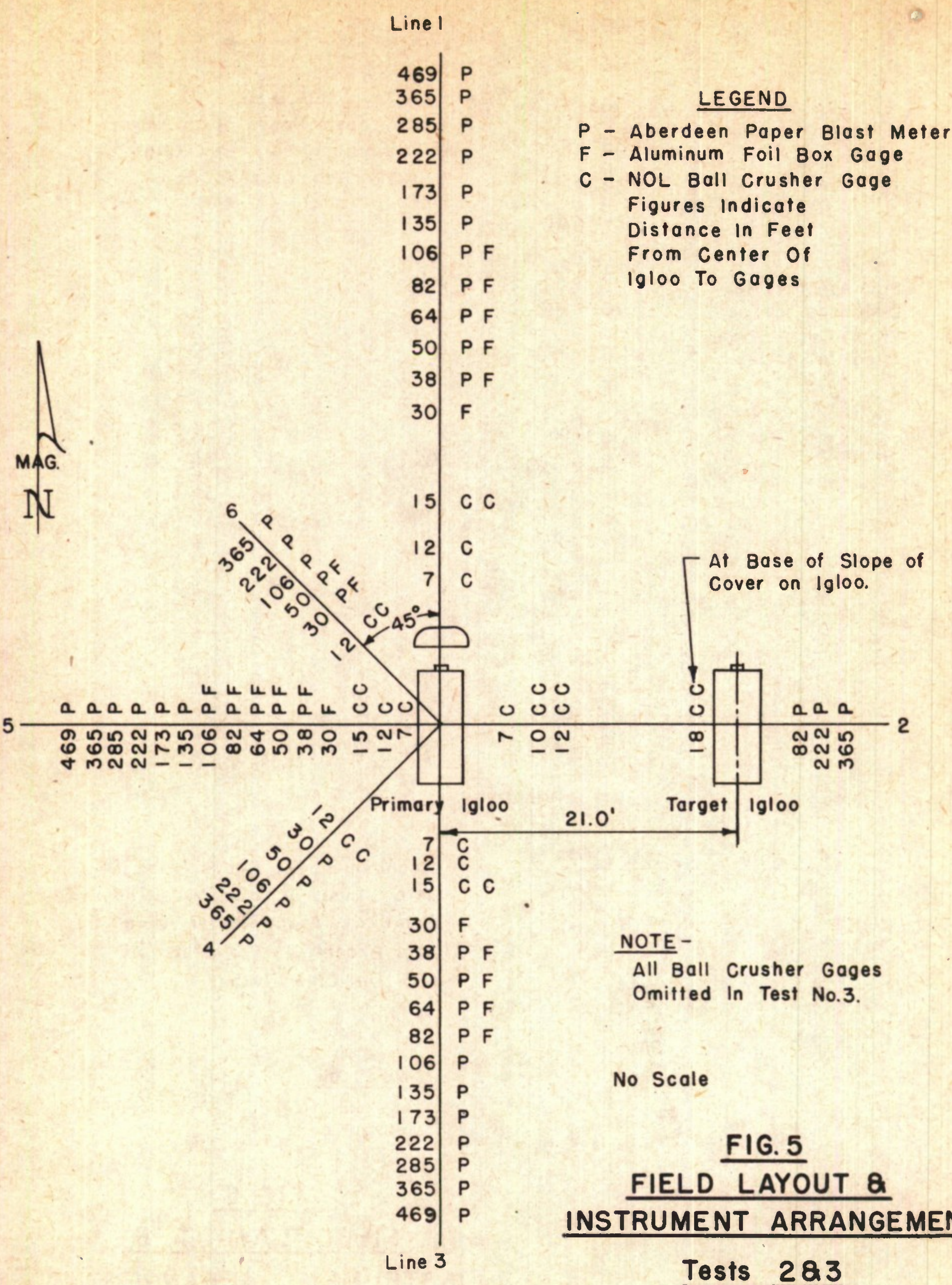


FIG. 5

FIELD LAYOUT & INSTRUMENT ARRANGEMENT

Tests 2&3

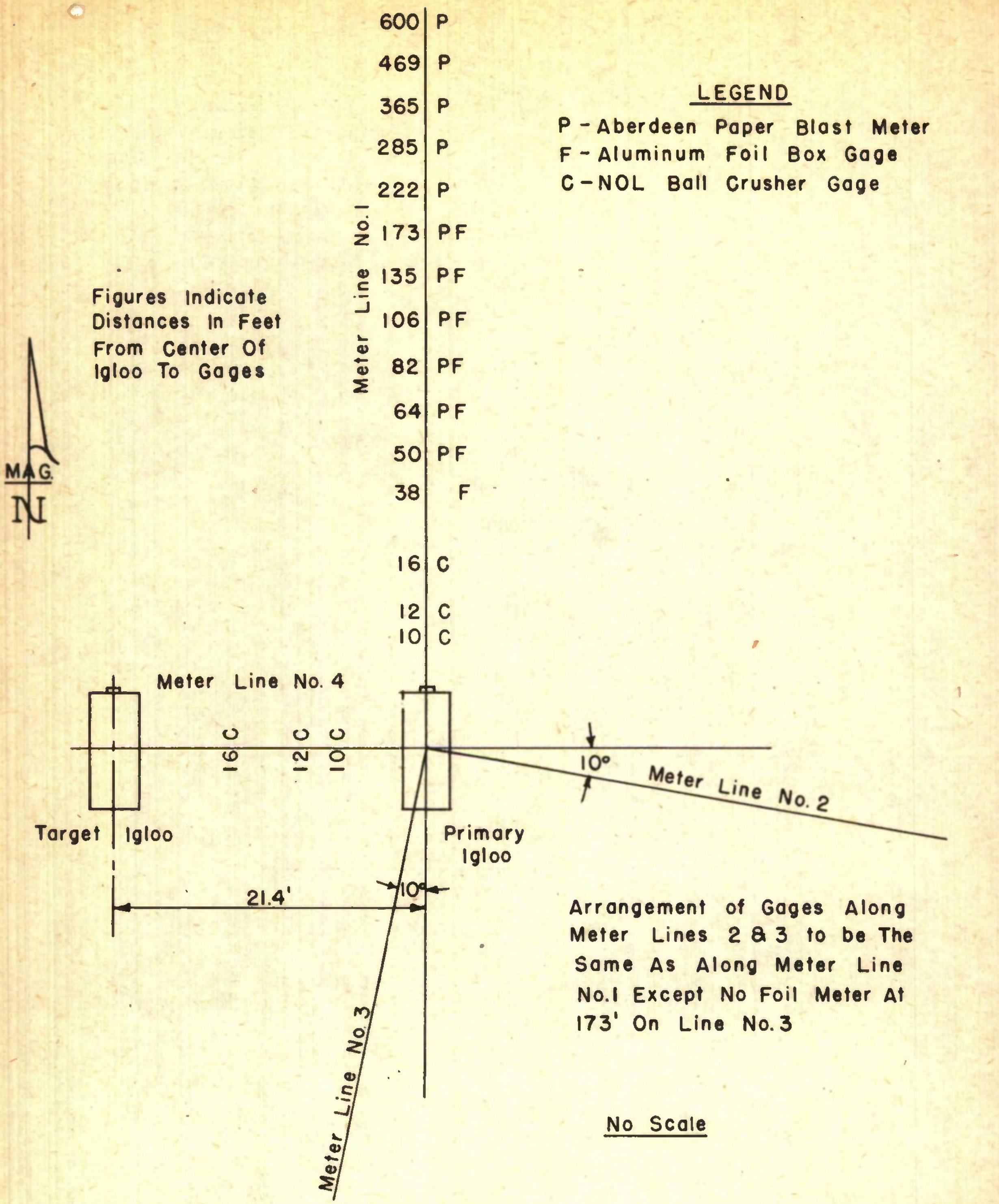


FIG. 6
FIELD LAYOUT &
INSTRUMENT ARRANGEMENT
Test 4 & 5

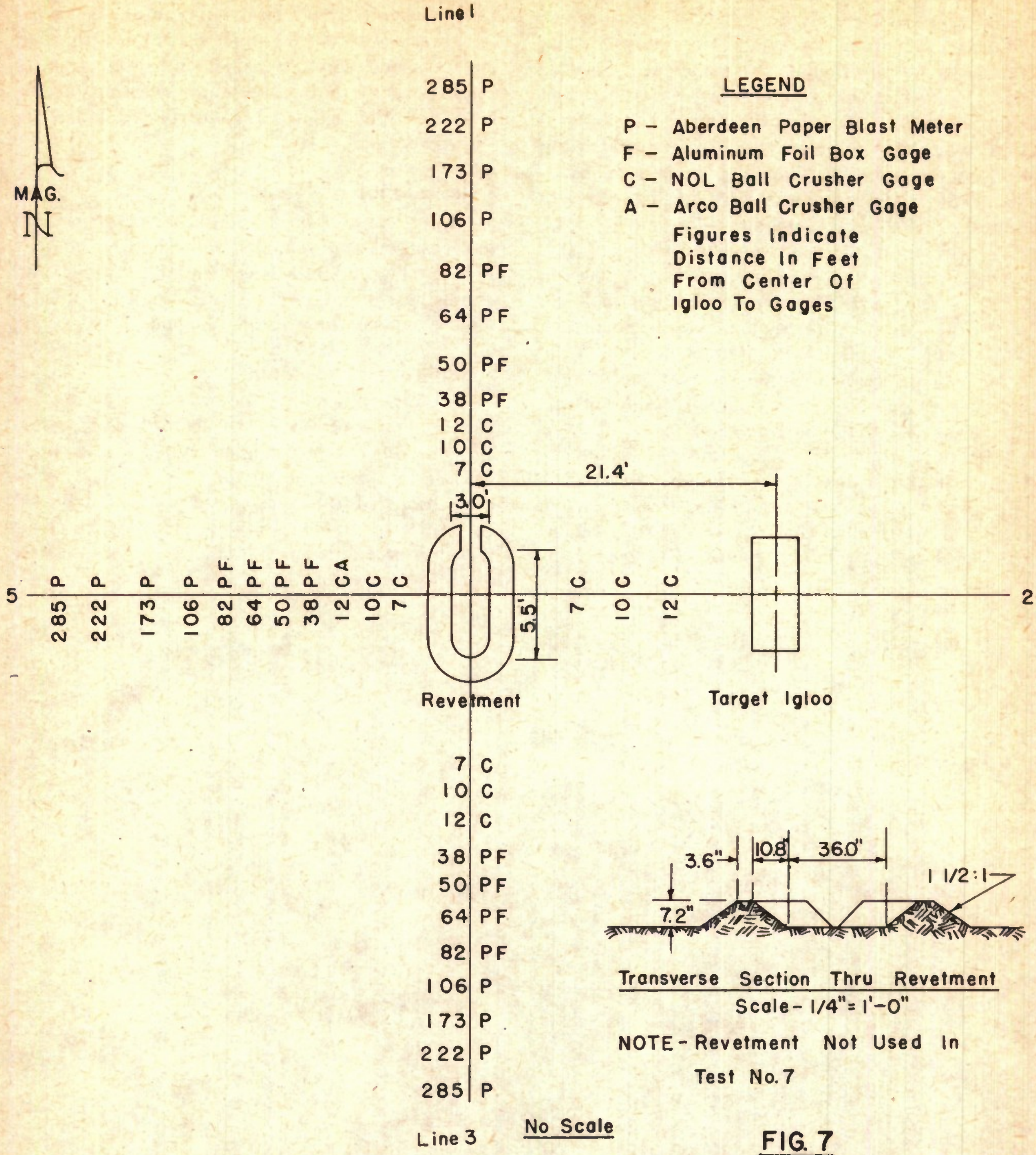


FIG. 7
FIELD LAYOUT &
INSTRUMENT ARRANGEMENT
Tests 6 & 7

3. Description of Model Igloos

For illustration, see photograph, figure 8. The models were constructed to one-tenth linear scale after standard Army and Navy prototypes. Some modification was made necessary by the small size of the model, the principal difference lying in the fact that the arch barrel was mounted on a slab which served both as floor and foundation, whereas the prototype has deeper footing walls and a separate floor slab poured on earth fill. The model was entirely of mortar concrete reinforced with single layers of 4-by-4-inch No. 13 steel wire mesh. Compressive strengths of test cylinders of the concrete ranged from 1,960 to 3,415 p. s. i. at 7 days and from 2,840 to 4,380 p. s. i. at 28 days. Further increases in strength were recorded as a result of later breaks, 5,250 p. s. i. being reached at 95 days in the case of cylinders from one igloo. Some of the important dimensions of the model were: Inside radius of semicircular arch, $15\frac{3}{4}$ inches; outside radius, 17 inches; thickness at crown, 0.60 inch; thickness at spring section, approximately $1\frac{1}{4}$ inches; inside length, 8 feet 0 inches; thickness of end walls, 1 inch; thickness of base slab, $\frac{5}{8}$ inch. The arch reinforcement was $\frac{1}{8}$ inch from the outer surface, and that of the base the same distance from the bottom surface. The door was of $\frac{1}{8}$-inch sheet steel over an 8-by-8-inch opening in one end wall, held in place by two $\frac{3}{16}$-inch stove bolts through the door and through a $\frac{1}{2}$-inch bar channel 10 inches long at midheight of the opening on the inside of the igloo. For further details, see reference 5, part VII.

4. Installation of Igloos

Before setting each igloo in place, vegetation and loose soil were removed to a depth of about 2 inches. The subgrade was then made as level and true as possible in order to furnish a firm continuous bearing for the base of the igloo.

5. Earth Cover on Igloos

The amount and shape of earth cover on the primary igloos varied in the first five tests, while the cover on the target igloos remained constant at the scale reproduction of the standard. For illustrations of the various shapes, see figure 9. The following table gives the weight of earth cover in each shot, the Shape Number from figure 9, and

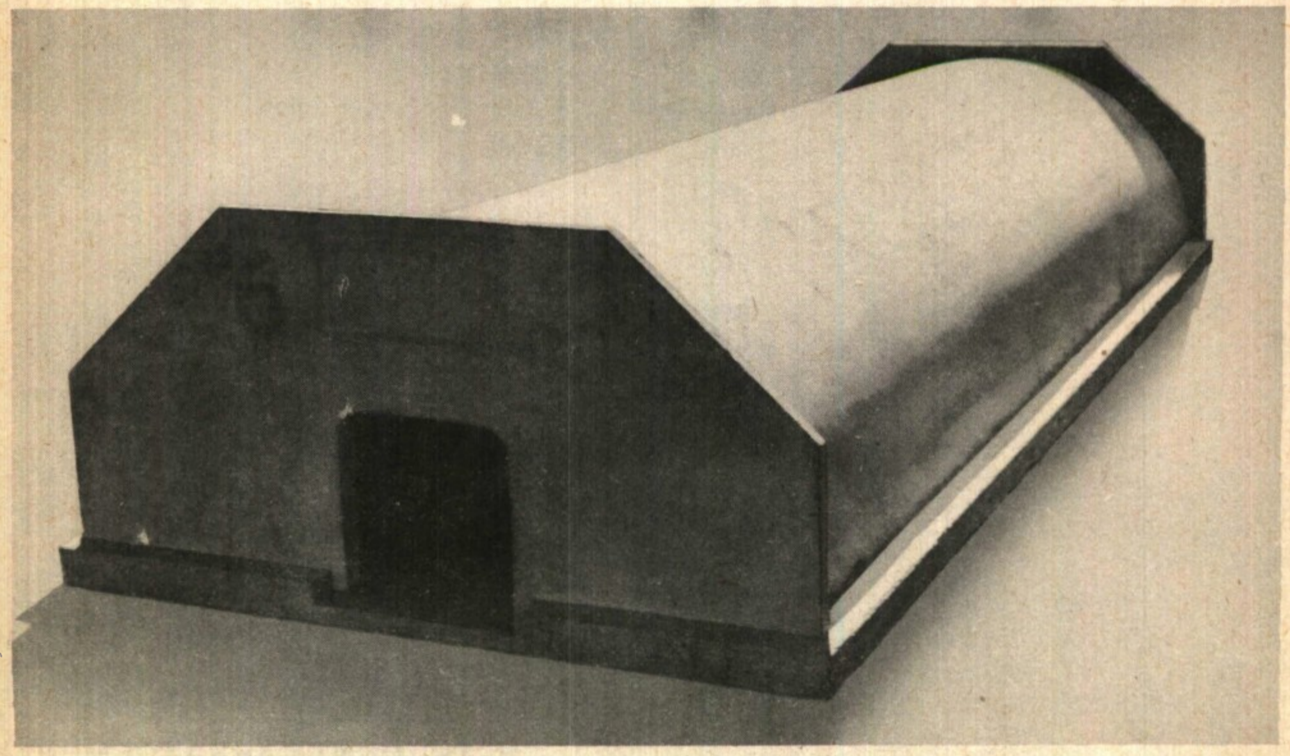
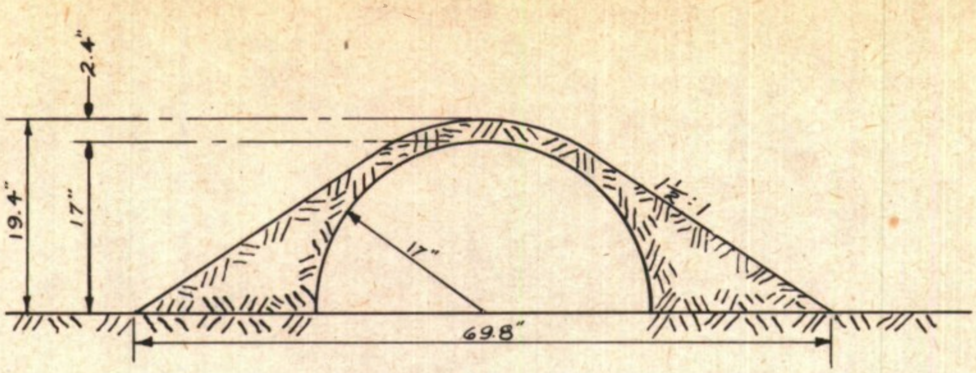
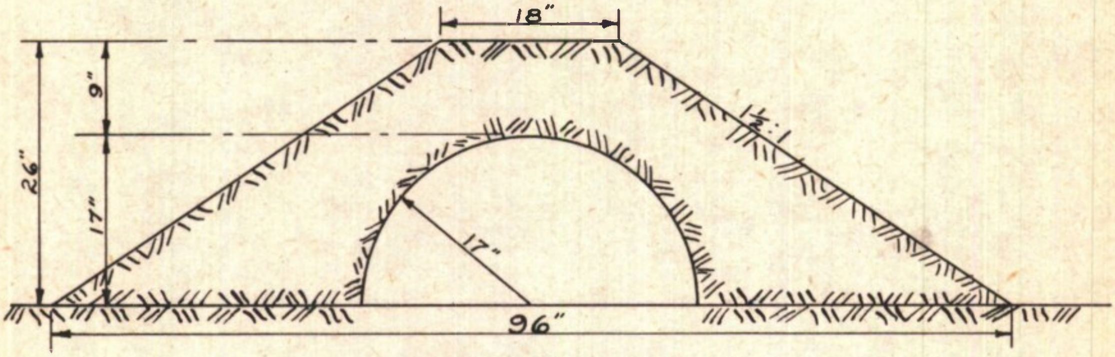


Figure 8. View of a model igloo.



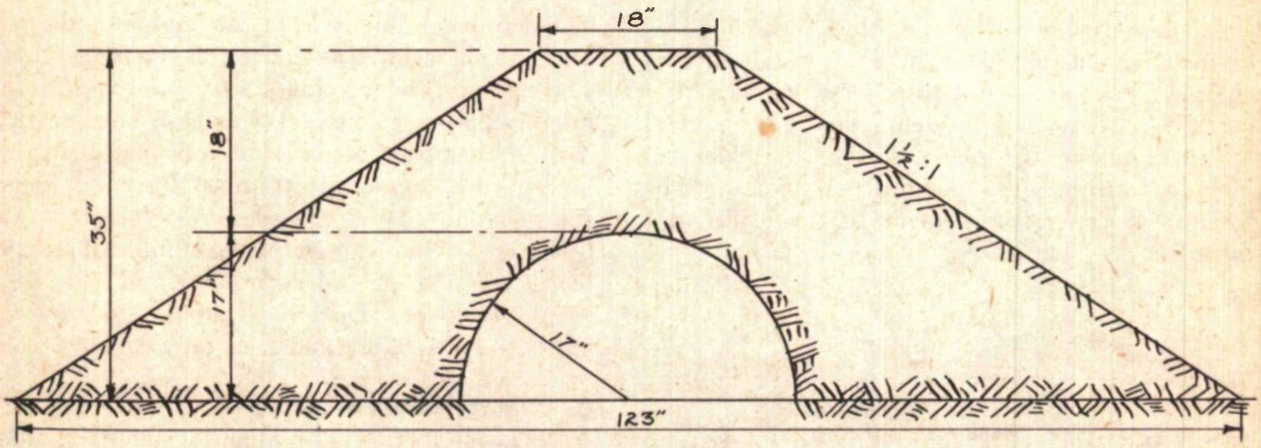
SHAPE NO.1 - STANDARD

Crown cover equivalent to 2'-0"



SHAPE NO.2 - FLAT TOP

Crown cover equivalent to 7'-6"



SHAPE NO.3 - FLAT TOP

Crown cover equivalent to 15'-0"

FIG. 9

CROSS-SECTIONS OF EARTH COVER FOR MODEL IGLOOS

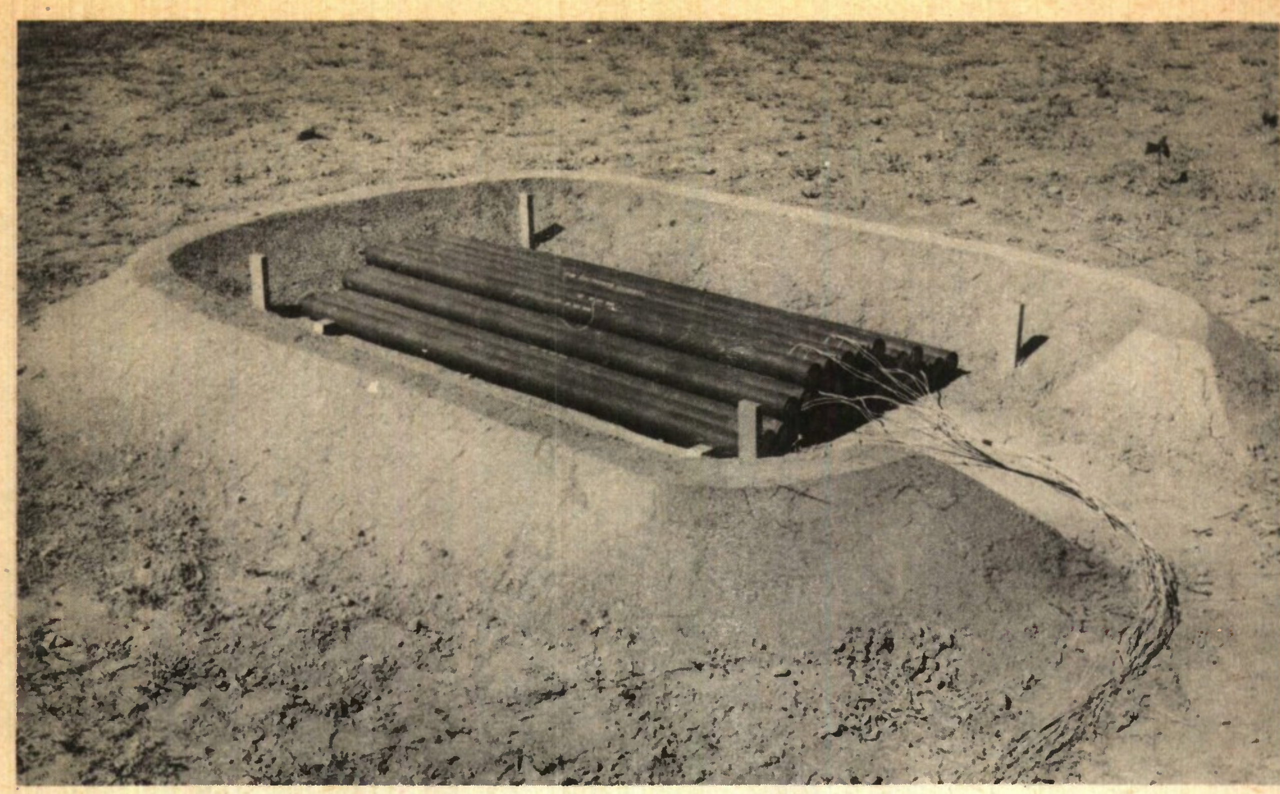


Figure 10. Pile of bangalore torpedoes in revetment making up charge for Shot 6.

the "cover-charge ratio," i. e., the weight of cover divided by the net pounds of explosives in the charge. For purposes of these tests, the weight of earth cover is arbitrarily defined as the weight of all earth above the plane of the subgrade and included within the side and end slopes. The weight of concrete or door barricades is not included.

TABLE I

Shot	Shape No. (fig. 9)	Weight of earth cover (pounds)	Cover-charge ratio
1	[1] 1	2,740	11.0
2	2	6,240	25.0
3	3	12,640	50.6
4	1	2,740	5.5
5	2	6,160	12.3

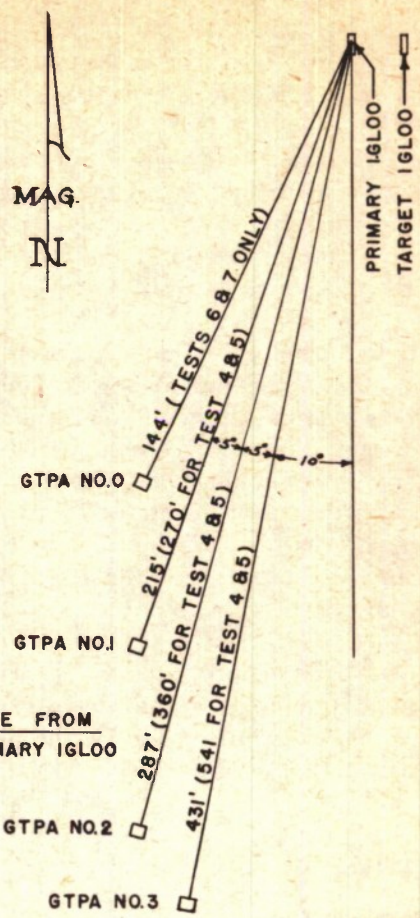
[1] Standard.

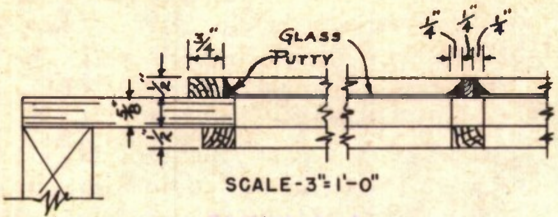
The soil was brought from the source of the soil used in constructing the cover on the large igloos. The material, which was a silty sand containing roughly 20 percent gravel, was moistened so that it would compact readily and was placed in thin layers, each layer being tamped by hand before the succeeding layer was placed. Placement was by batches of known weight, the number of batches being counted in order to arrive at the total weight of cover. Door barricades were provided in Shots 1 through 3 and 1–A, only.

6. Primary Charges

The net high-explosive charge weights were 250 pounds in Shots 1 through 3, 500 pounds in Shots 4 and 5, and 250 pounds in Shots 6, 7, and 1–A. The charges were made up of bangalore torpedoes, Army type M1A1. The torpedo is in the form of a tube 5 feet long by 2⅛ inches in diameter, a 4-inch length at each end being loaded with TNT, and the central portion loaded with 80–20 amatol. Total charge weight is 8.92 pounds. The charge/weight ratio is about 68 percent. To make up a 250-pound charge, 28 torpedoes were placed in a

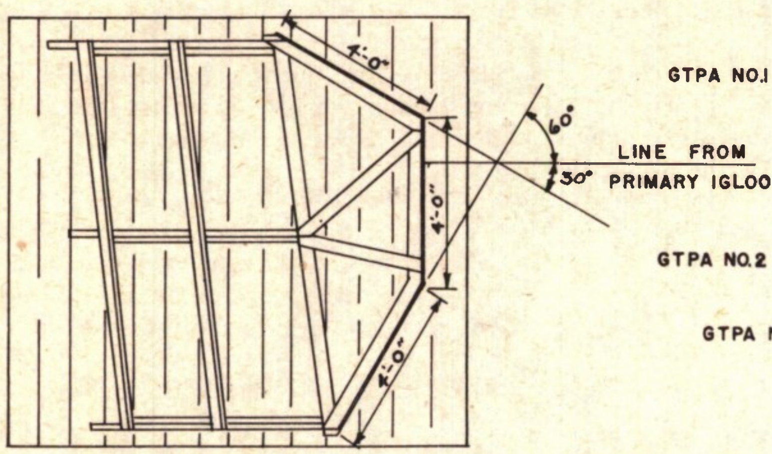
LOCATION PLAN



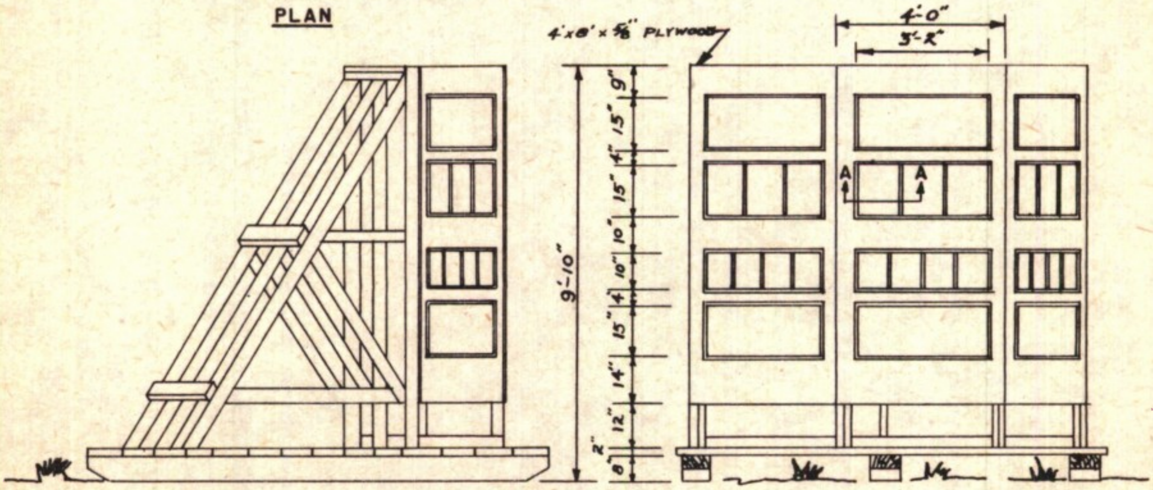


SCALE-3"=1'-0"

Section A–A
CONSTRUCTION OF STILE, MUNTIN AND METHOD OF GLAZING.



PLAN



SIDE ELEVATION

SCALE-1/4"=1'-0"

FRONT ELEVATION

GLASS TEST PANEL ASSEMBLY

FIG. 11
ARRANGEMENT FOR GLASS TESTS

pyramidal pile of 3 layers, having 14 torpedoes on the bottom, 9 on the second, and 5 on the top layer. To make up a 500-pound charge, 56 torpedoes were placed in a pyramidal pile of 5 layers, with 14 on the bottom, 13 on the second, 12 on the third, 11 on the fourth, and 6 on the fifth layer. The piles were placed symmetrically with their centers at the centers of the primary igloos. The 250-pound open charges were made up of piles identical to those used in the igloos, the charge being arranged symmetrically within the revetment in the case of Shot 6. The charges were primed by placing special engineer's electric blasting caps in the cap wells of a fourth of the bangalores chosen at random, and connecting the caps in series. Firing was accomplished by means of a 30-cap blasting machine located at the firing station about 500 feet distant, a 2/c No. 18 AWG firing cable being used to connect the 2 locations. Figure 10 is a photograph of the pile of bangalores making up the charge in Shot 6.

7. Secondary Charges

Each target igloo was loaded with an inert charge equal to the gross weight of the corresponding primary charge. This charge was made up of lengths of 4-by-½-inch steel channel iron arranged in a pile of roughly the same shape and over-all dimensions as the pile of bangalores.

8. Window Glass Tests

In each shot, except 1–A, representations of windows glazed with common double strength, B quality, sheet glass were set up as illustrated by figure 11. Window assemblies were placed at three distances from the primary igloo in each shot as follows:

TABLE II

Shot No.	Distances from charge of glass test panel assemblies		
	(1) Feet	(2) Feet	(3) Feet
1	215	287	431
2	215	287	431
3	215	287	431
4	270	360	541
5	270	360	541
6	144	215	287
7	144	215	287

The glass test panel assembly contained three panels each with lights of three sizes as follows: 2 lights 38 by 15 inches, 3 lights 12 by 15 inches and 4 lights 9 by 10 inches. Each panel was oriented at a different angle; the plane of the glass making angles of 30°, 60°, and 90° with the line from the charge to the panel. The distances in Shots 4 and 5 are one-tenth of the distances at which windows of test barracks buildings were to be exposed to blast in the full-scale igloo tests. The distances in each test were one-tenth of American Table of Distances inhabited building safety distances as follows: Tests 1 to 3: Panel 1, barricaded distance; Panel 2, two-thirds unbarricaded distance; Panel 3, full unbarricaded distance; all based on 250,000 net pounds of high explosives. Tests 4 and 5: Panel 1, barricaded distance; Panel 2, two-thirds unbarricaded distance; Panel 3, full unbarricaded distance; all based on 500,000 net pounds of high explosives. Tests 6 and 7: Panel 0, one-third unbarricaded distance; Panel 1, barricaded distance; Panel 2, two-thirds unbarricaded distance; based on 250,000 pounds. Barricaded distances are one-half unbarricaded distances.

9. Instrumentation and Observations

A. Air Blast Measurements. Air blast from the explosions was measured by Naval Ordnance Laboratory ball crusher gages and a modification thereof, foil diaphragm gages of a type used by the Underwater Explosives Research Laboratory of Woods Hole, Mass., and Aberdeen Proving Ground paper blast meters. The positions of these gages in the tests are shown in figures 4 through 7. The gages are illustrated in figures 12, 13, and 14, and are described as follows:

(1) NOL Ball Crusher Gage. This gage measures peak blast pressures, and was used to measure the high pressures relatively close to the charge. It consists of a heavy cylindrical brass housing approximately 1½ inches in diameter by 1½ inches long, containing a hardened steel piston one end of which is exposed to external pressure, the other end contacting a specially heat-treated copper ball resting on a hardened copper alloy or steel anvil. When the excess pressure behind the shock front impinges on the piston, the copper ball is deformed and the amount of this deformation is a measure of the force exerted. The diameter of the ball used in these tests was ⁵⁄₃₂ inch and the dynamic calibration constants for this size of ball when the gage is used in air were calculated as described in appendix B.

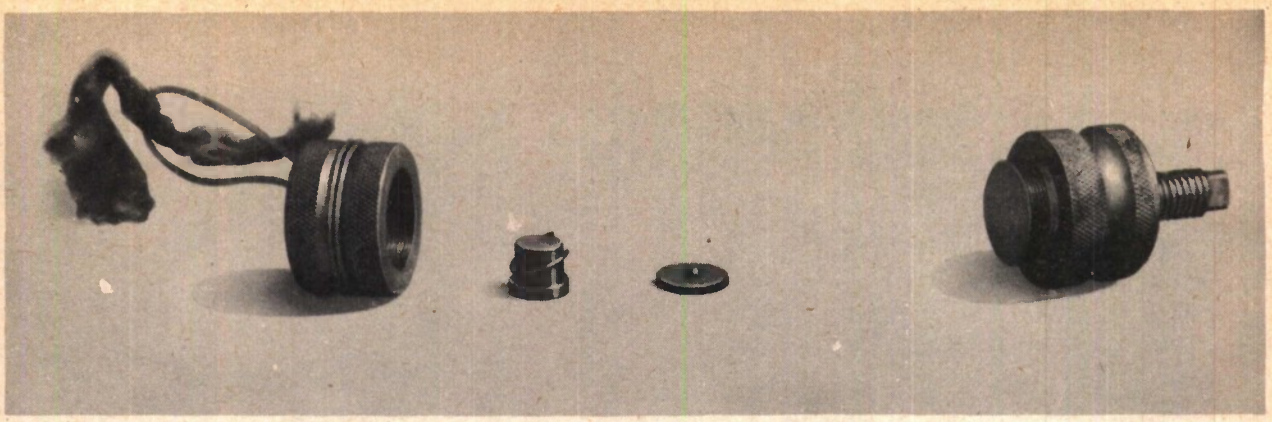
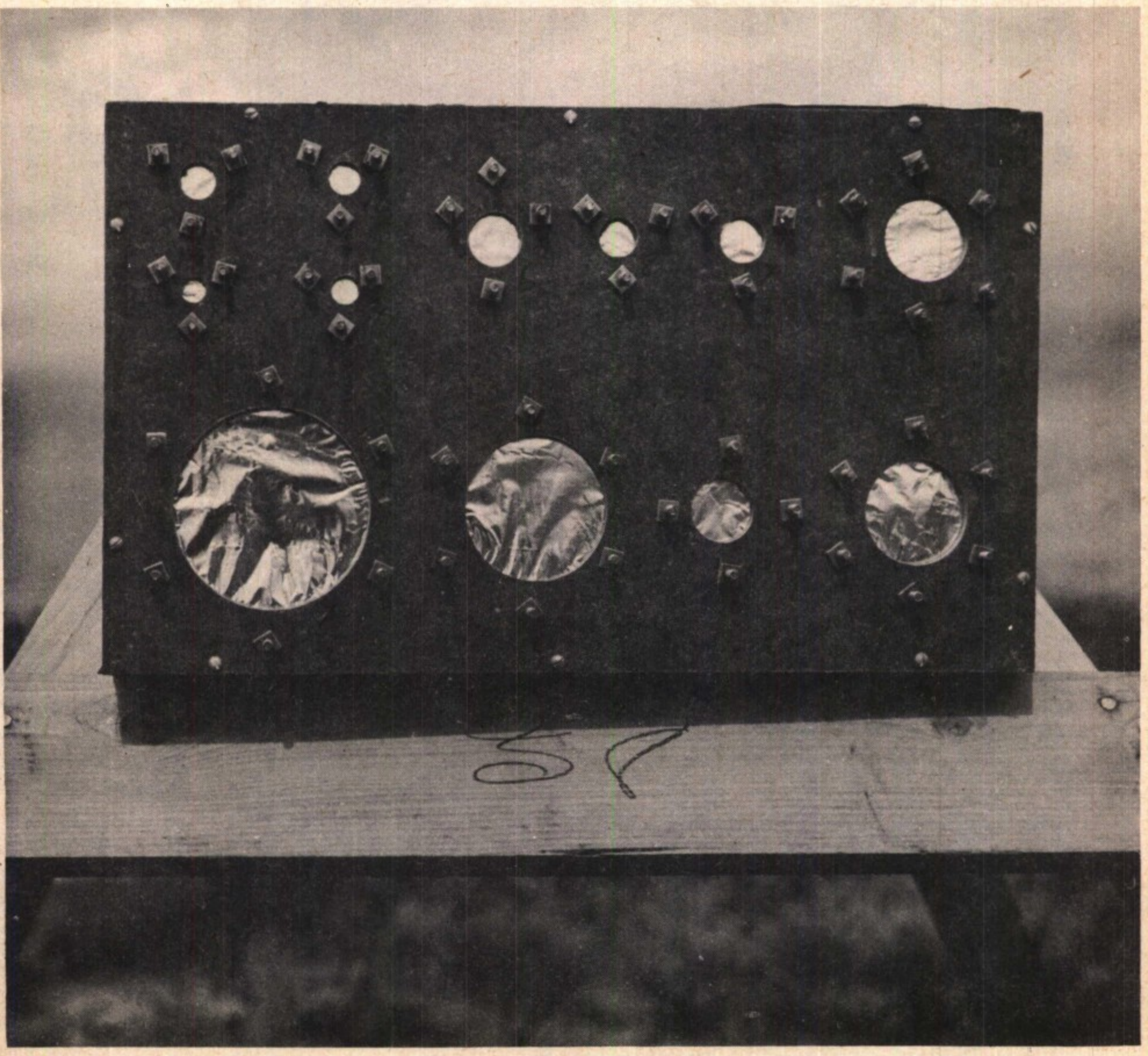


Figure 12. NOL ball crusher gage (exploded view).

Figure 13. Aluminum foil blast meter.



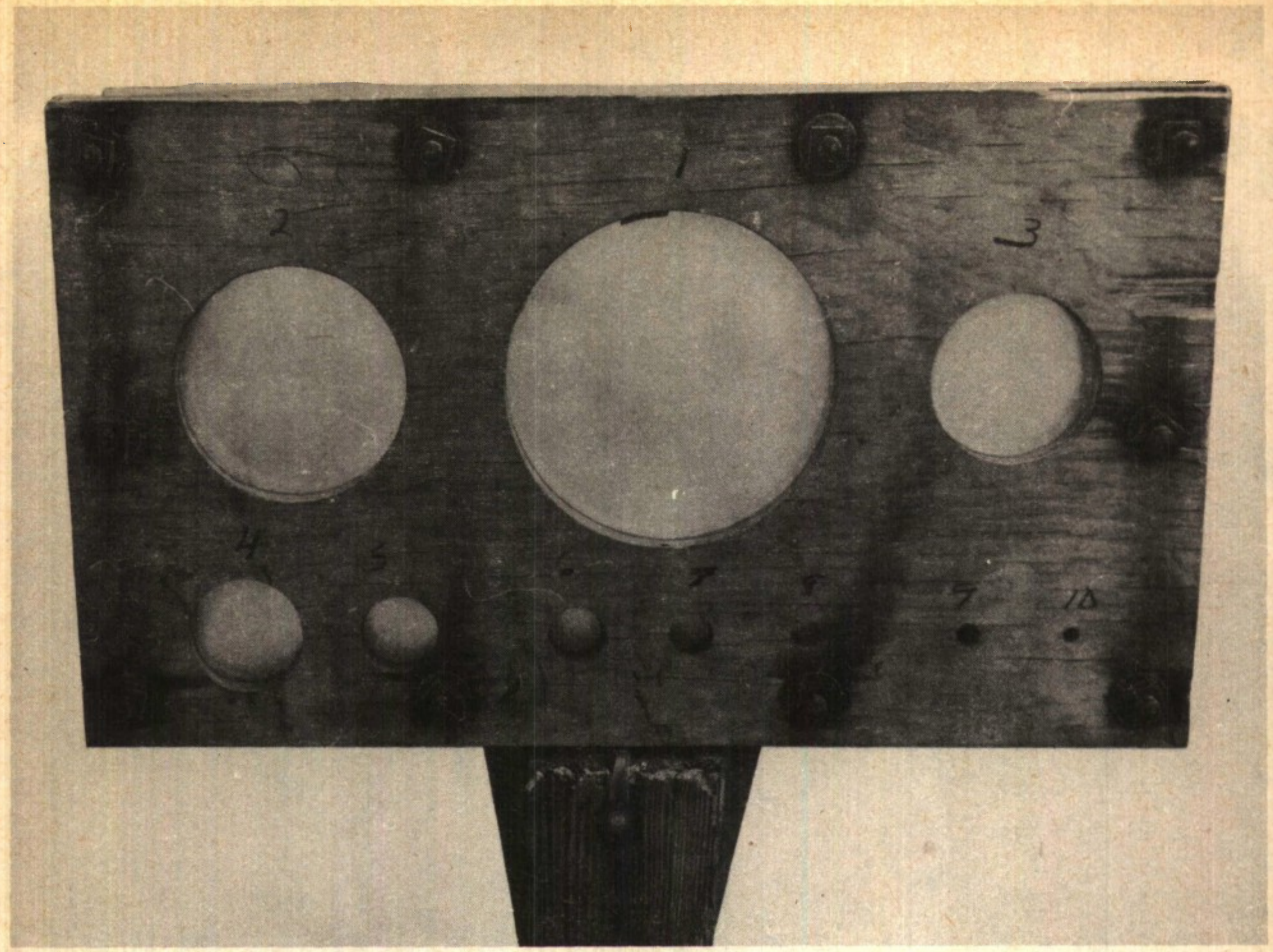


Figure 14. Aberdeen paper blast meter.

The gages were mounted in "side-on" orientation, i. e., with the plane of the face of the piston parallel to a line from the detonated charge to the gage. The gage was partly buried in the ground, with the piston exposed flush with the surface, and the body fastened into the top of a 2 by 4-inch wood stake driven about a foot into the ground vertically beneath it, in order to provide inertia against movement during impingement of the pressure wave.

During the tests, it became apparent that satisfactory readings were not being obtained with these gages, as the pressures were at or below the lower limit of the readable range of this type of gage. An attempt was made to eliminate this difficulty by making a new gage in the Arco shop which had a piston diameter of 1.128 inches or a face of 1 square inch, thus causing approximately 5 times as much force to impinge on the copper ball as in the original gage. This gage, called the "Arco Ball Crusher Gage," gave readable deformations of the copper balls.

(2) Foil blast meter. This meter also measures peak blast pressure. It consists of a heavy plywood box, 2 feet by 17 inches by 10 inches, one 17-inch by 10-inch face being covered by inner and outer orifice plates of ¼-inch tempered masonite. The orifice plate contains 12 holes of various sizes, the diameters of which are given in table III. The diaphragm material which is mounted between the inner and outer orifice plates, is soft annealed aluminum (2SO) foil 0.001 inch thick. The meter is read by recording the smallest hole in which the foil is ruptured by the blast. A calibration was obtained by setting up a number of gages at various distances from standard 100-

pound cylindrical charges of TNT manufactured at the Picatinny Arsenal to specifications of the Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland. The pressure-distance relation for these charges detonated in air was determined by the Ballistic Research Laboratories and the information made available for the calibration of the foil blast meters used in these tests. Five shots were made in the calibration and the averaged results are tabulated in table III. The calibration is described in appendix B. These meters, commonly called "box gages" in the field, were mounted on wooden stands or "horses," in order to clear the desert vegetation, and were set with the orifice plates "side-on" to the blast. The shipment of foil used in these tests was received in a rather wrinkled condition and it was found impossible to smooth out all the wrinkles in loading the meters. The wrinkling undoubtedly contributed to the scatter of the readings.

TABLE III

Diameters of orifices in plywood box diaphragm blast meter, and hydrostatic peak pressures corresponding to diaphragms ruptured when loaded with 0.001-inch 2SO aluminum foil and mounted side-on to the blast

Orifice No.	Diameter (inches)	Peak blast pressure, p. s. i.
1	3.52	3.3
2	2.58	4.4
3	1.97	5.6
4	1.49	7.2
5	1.15	9.2
6	.92	11.3
7	.84	12.3
8	.71	14.3
9	.63	16.0
10	.61	16.4
11	.51	19.3
12	.46	21.3

(3) Aberdeen paper blast meter. This meter also measures peak blast pressure. It comprises two 20-by-11-inch pieces of ¾-inch plywood bolted together around their edges and containing ten orifices of various sizes, the diameters of which are given in table IV. The paper used in these tests was "Rap-in-Wax" waxed paper made by the Rap-in-Wax Paper Company of Minneapolis, Minnesota, and was 0.0013 inch thick. The calibration of this paper was made by the Ballistic Research Laboratories and published in reference 8, part VII. These meters were mounted on stakes driven vertically in the ground, at a sufficient height to clear the desert vegetation, and were oriented "face-on" to the blast, i. e., the plane of the diaphragm was normal to the line from the detonated charge to the meter. Although mounted "face-on," these gages were calibrated to give the equivalent "side-on" or hydrostatic peak pressure.

Reference 8 stated that the standard error of estimate of the peak pressure is approximately 26 percent of the peak pressure.

B. Transient Displacements of the Models.—An effort was made to obtain relative indications of the maximum upward movement of the floor of the target igloo and of the difference between the closest approach of floor and ceiling during the test and the normal floor-to-ceiling distance. These readings were taken on the longitudinal centerline at points about 16 inches inside the doorway. Two types of gages, pictured in figures 15a and 15b, were used. The operation of these gages is apparent from the illustrations.

C. Permanent Displacements.—Measurement of each target igloo from stationary points before and after the shot were made to detect any appreciable permanent displacement, both horizontal and vertical. A grid or network was made of surveyor's stakes driven in flush with the ground 5 feet apart to a distance of 20 feet from the charge or primary igloo and surrounding it, and the distances between the stakes and their elevations before and after the shot were measured and compared.

D. Craters.—Each crater was photographed, measured, and its plan view and profiles of two sections normal to each other were drawn.

E. Damage to Models.—Following each explosion the target igloo was carefully inspected and sketches made of cracks or evidences of more

severe damage. Photographs were taken to record typical instances of damage, both before and after the earth cover was removed.

F. Motion Pictures.—A 16-mm. camera operating at 16 frames per second was used to record scenes during preparations for the tests, the shots themselves (at 64 frames per second), and scenes of the craters and damaged target igloos following these tests. A 16-mm. camera equipped with a 2½-inch telephoto lens photographed the explosion at 64 frames per second. These films are in the files of the Army-Navy Explosives Safety Board.

TABLE IV

Diameters of orifices in Aberdeen Paper Blast Meter, and hydrostatic peak blast pressures corresponding to diaphragms ruptured when loaded with "Rap-in-Wax" waxed paper

Orifice No.	Diameter (inches)	Peak blast pressure, p. s. i.[1] from–to
1	5.38	0.4– 0.6
2	3.75	.6– .8
3	2.75	.8– 1.2
4	1.88	1.2– 1.8
5	1.25	1.8– 2.7
6	.88	2.7– 3.6
7	.62	3.6– 5.8
8	.50	5.8– 7.7
9	.31	7.7–12.6
10	.25	12.6–>12.6

[1] The fact that the foil gage calibration is given in single pressures, while that of the paper meters is in ranges, is due to differences in handling and interpreting the data at Aberdeen and at Arco. To be strictly correct the Aberdeen data should be reworked in the manner of the Arco treatment (or vice versa); however, resulting changes in final pressures would be small and conclusions would not be affected.

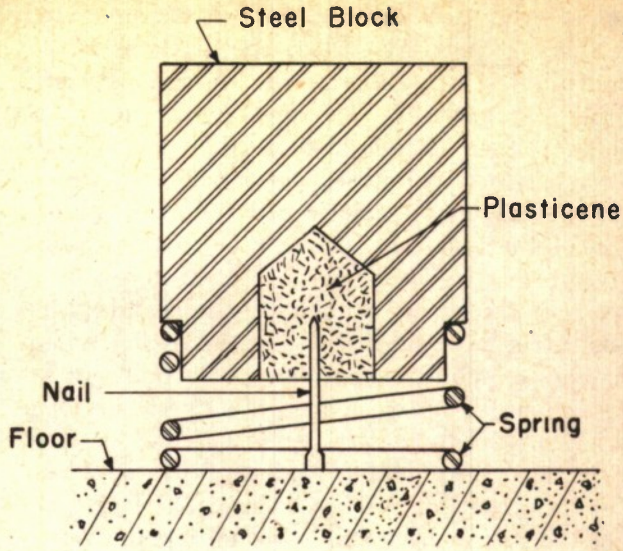


FIG. 15 (a)

FLOOR DEFLECTION GAUGE

Maximum Deflection of Floor Is Equal To Deflection of Nail

Scale - Full Size

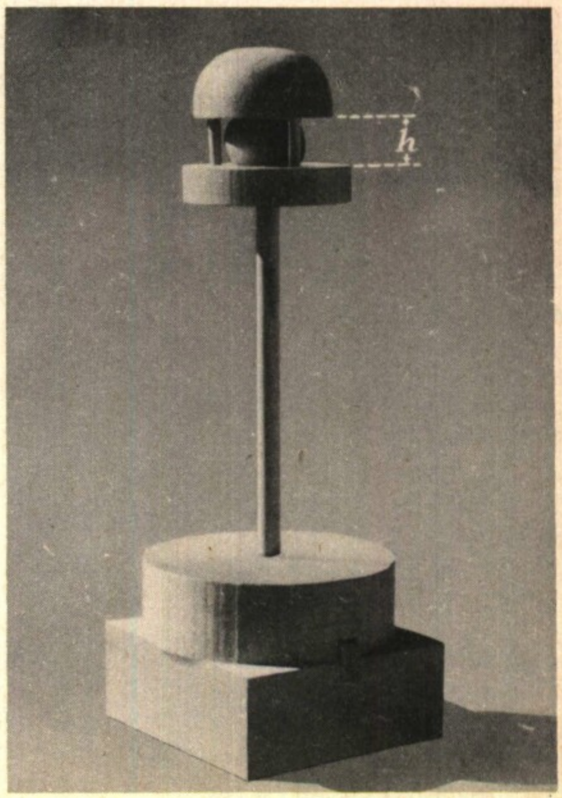


Figure 15 (b). Arch deflection gage. Change in "h" measures approach of arch to floor.

PART IV. RESULTS

1. Test No. 1, fired at 1100, 30 July 1946

A. Field Arrangement. Primary and target igloos as diagrammed by figure 4 and illustrated by the photographs, figures 16, 17, and 18. Standard earth cover on both igloos. Charges, 250 pounds, amatol.

B. Description of Explosion. A high order detonation, characterized by a brilliant yellowish-white flash followed immediately by a bulbous light brown cloud which shot rapidly up to about 300 feet, and then dissipated to the westward in the light (about 10 m. p. h.) breeze. The cloud was composed largely of soil particles from the site. No ground shock was noticed. The air shock wave and a loud report arrived simultaneously at the firing station 500 feet to the southeast. The air shock seemed moderate. The shot was not fired on the first attempt, as apparently there were defects in the firing cable which had not been disclosed by testing with the galvanometer. After several futile attempts, four of the caps were disconnected and the shot was successfully fired with the three remaining caps. The detonation was, however, complete.

C. Crater. The crater was nearly round, being 15.8 feet in diameter. See figure 19 for its plan and profiles. Figure 20 is a photograph of this crater. The shape of the deeper part was rectangular, about 6 feet long in the direction of the axis of the igloo and about 8 feet transversely. This "crater within a crater" appeared to bear some relation to the pile of bangalore torpedoes which had formed the charge.

D. Damage to Target Igloo.—The damage was slight. A fine hairline seasoning crack which had existed prior to the explosion opened up to 1/32 inch at its middle. This crack was in a horizontal position on the near side (i. e., the side nearest the explosion) of the arch barrel, 6 inches above the base. It was approximately 6 feet long and extended through to the inner surface. The lower edge of the arch barrel on the near side was cracked away from the base slab and inward about 1/16 inch but was not raised. This cracking extended throughout the middle third of the barrel length. The door, rear end section, and base slab were undamaged. The face of the front end wall was cracked vertically on the near side. The earth cover was left rough and had subsided somewhat, exposing the top of the rear end wall. See the photograph, figure 21. For an illustration of the cracking of the igloo, see figure 22.

E. Glass Breakage.—Two lower large panes broke in the nearest (215 ft.) glass test panel assembly, one in the panel oriented 90° to the line from the explosion to the panel, or facing the explosion, and the other in the panel oriented at 60°. No other glass breakage occurred. Figure 23 is a photograph of the lower portion of the glass test panel assembly, illustrating the breakage. The field notes, which graphically portray the breakage, are included in appendix A of this report. The fragments fell out toward the explosion and were found on the front part of the platform; there was evidently no "flying glass."

TABLE V
AVERAGE PERMANENT EARTH DISPLACEMENT IN INCHES, SHOT 1

Distance from center of charge, feet.

	8	13	18	23
Vertical......	+2.03	+0.68	+0.48	+0.23
Horizontal....	+4.93	+.98	+.12	+.09

(+means up and away from explosion.)

Figure 16. Primary (at right) and target igloos, Test 1.

Figure 17. Primary igloo, Test 1.

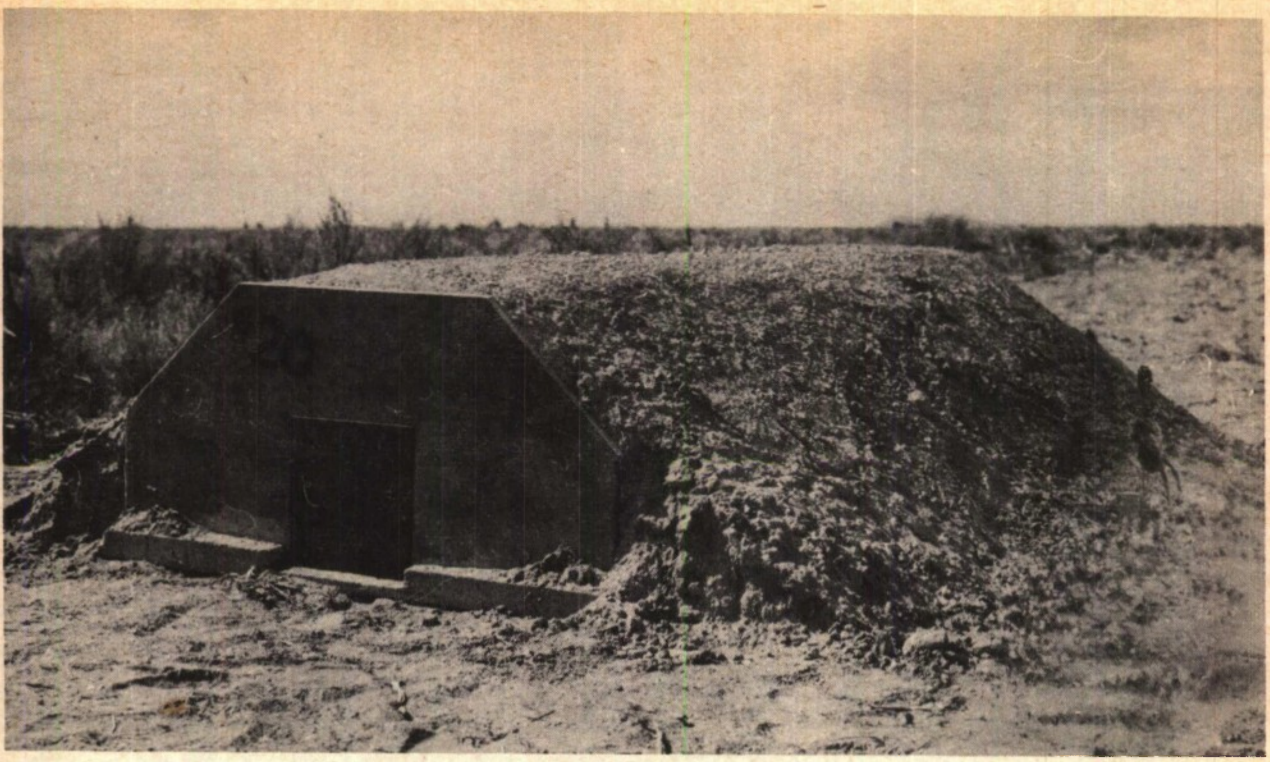


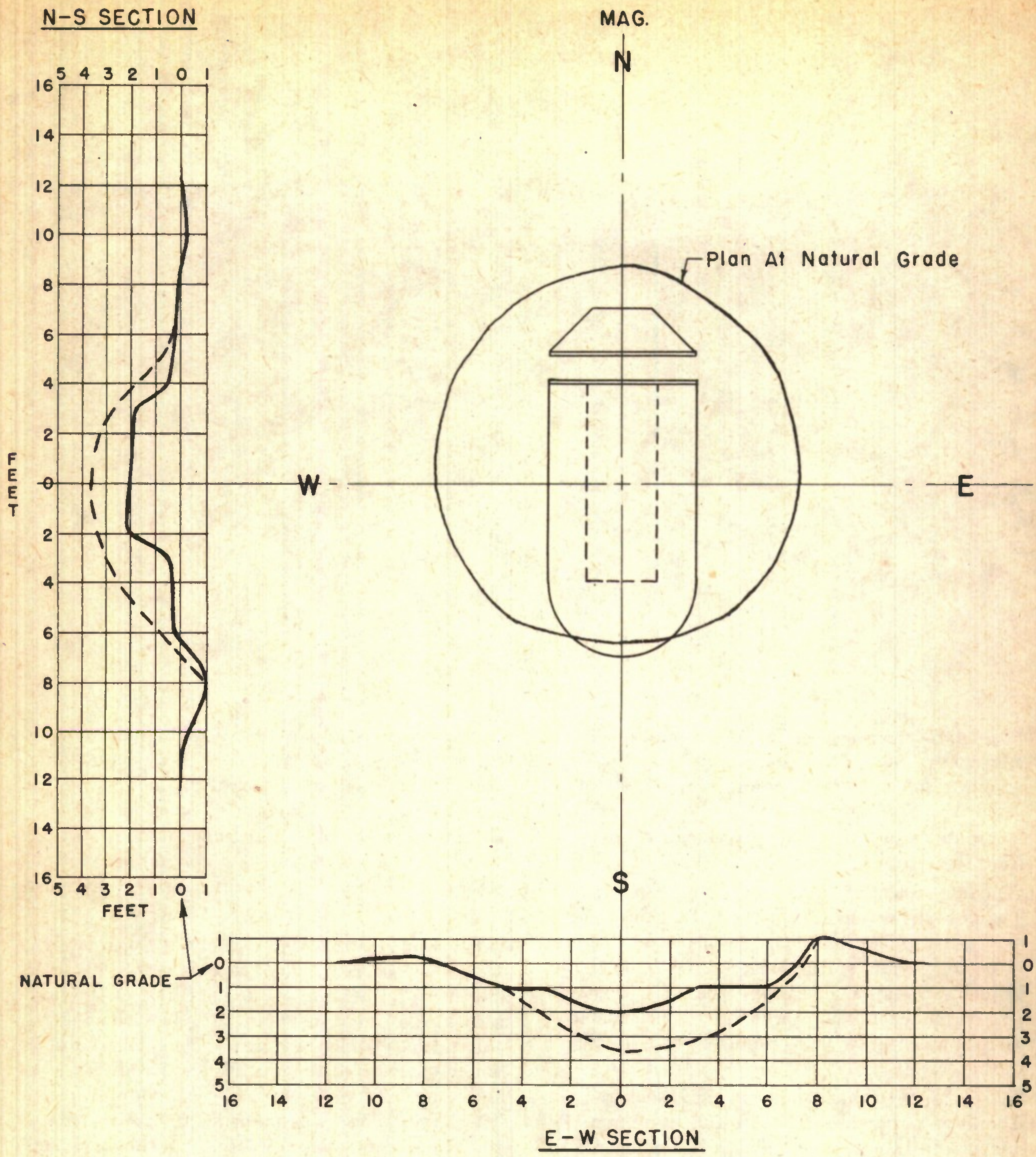
Figure 18. Target igloo, Test 1

F. Earth Displacement.—The ground surrounding the charge moved up and away from it. The amounts of the movements are tabulated in table V. See figures 69 and 70 for graphs of horizontal and vertical displacement vs. distance from the center of the charge.

G. Displacement of Target Igloo. (1) Transient: The floor deflection gage indicated a transient rise of $^{17}/_{32}$ inch. The arch-floor gage showed a decrease in ceiling height at the longitudinal centerline of $^{3}/_{32}$ inch. See appendix A for actual measurements. (2) Permanent: There was no visible displacement, but accurate measurements were not taken in this test.

H. Air Blast. Peak pressures as measured by Aberdeen paper blast meters and aluminum foil meters are tabulated in table VI and plotted on logarithmic graph paper in figure 24. Off the side of the primary igloo, pressures ranged from about 46 p. s. i. at 15 feet, to 0.5 p. s. i. at 400 feet. Results with the NOL ball crusher gages were unsatisfactory, the deformations of the copper balls being erratic and considerably less than deformations corresponding to the pressures which were believed to have existed. A possible explanation of the difficulty is that a slight hardening of the surface of the copper balls may have taken place since their heat treatment many months prior to the tests, with the result that the elastic limit was raised and permanent deformations proportionate to the stress imposed were not obtained. The readings obtained are tabulated in appendix A.

I. Fragmentation. A walking tour of the area within a 400-foot radius of the crater was made to obtain an impression of the character of the fragments and their distribution. The concrete of the primary igloo evidently had been almost wholly pulverized, for only a few large pieces, in and relatively near the crater, could be found. The largest piece was found in the south part of the crater, and was a section of the base slab about 12 inches long by 8 inches wide. A piece of the arch about 3 inches by 2 inches by 1 inch was found 125 feet to the north. Fragments of casing from the bangalore torpedoes were prevalent within 200 feet, and a few small pieces about 1 inch to 2 inches long were found from 350 to 400 feet away. A section of the igloo door was found 100 feet to the north.

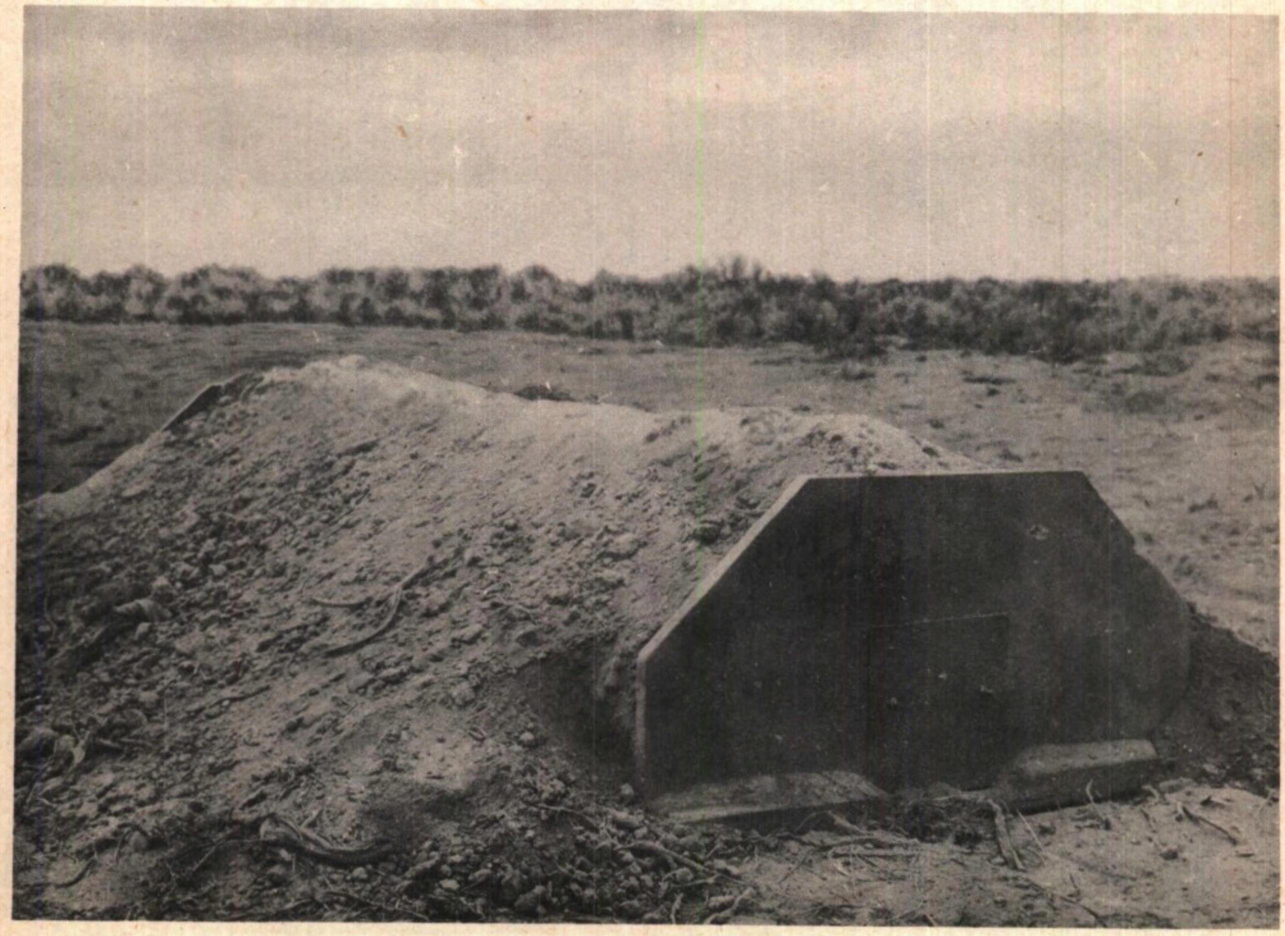


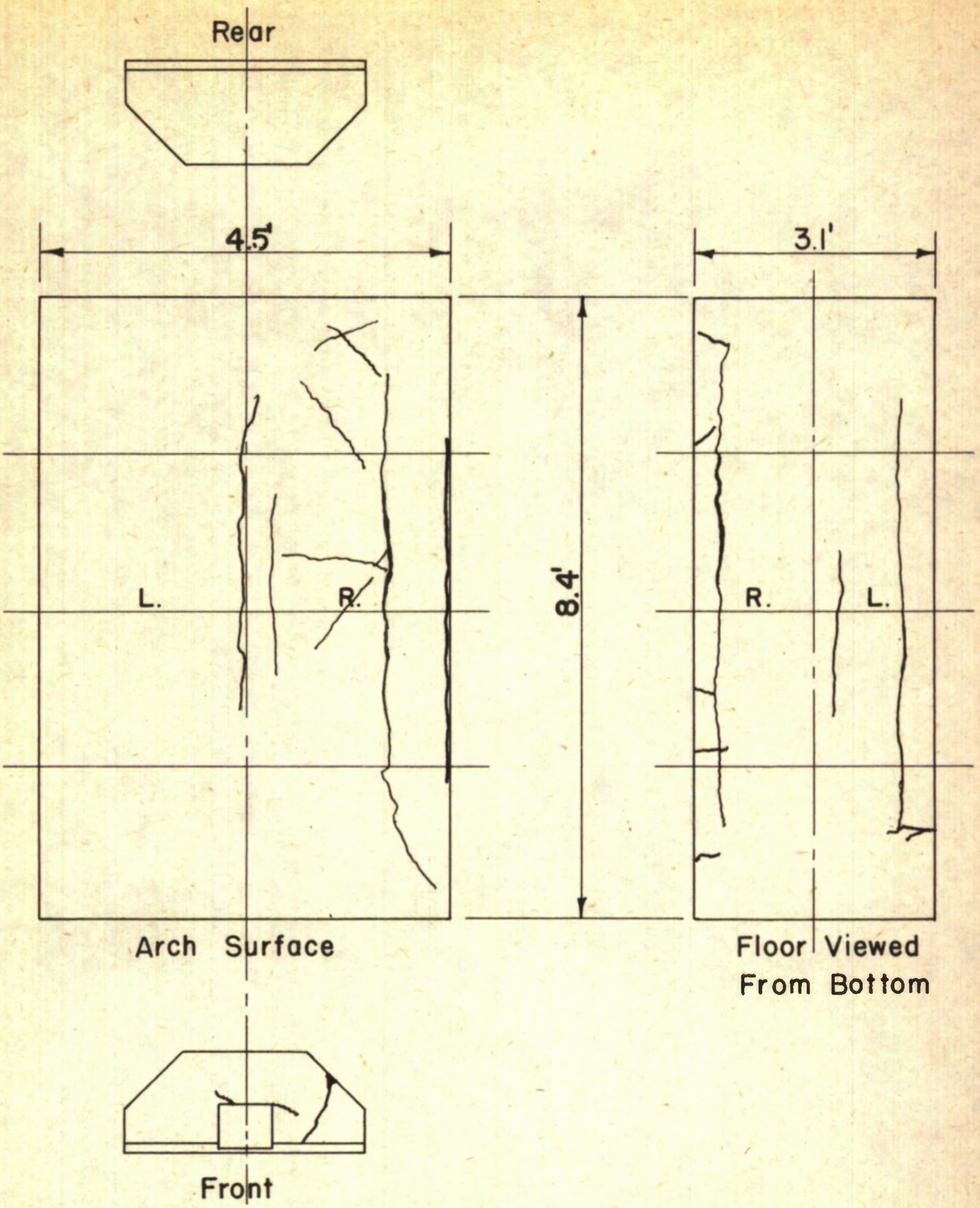
LEGEND
—— Apparent Crater
– – – Estimated True Crater

FIG.19
CRATER PROFILES
Model Test No. 1

Figure 20. Crater, Test 1.

Figure 21. Target igloo after shot, Test 1.





Shape I Earth Cover On Primary Igloo.

Charge Weight 250#

FIG. 22
DIAGRAM OF CRACKING
TARGET IGLOO
Model Test No. I

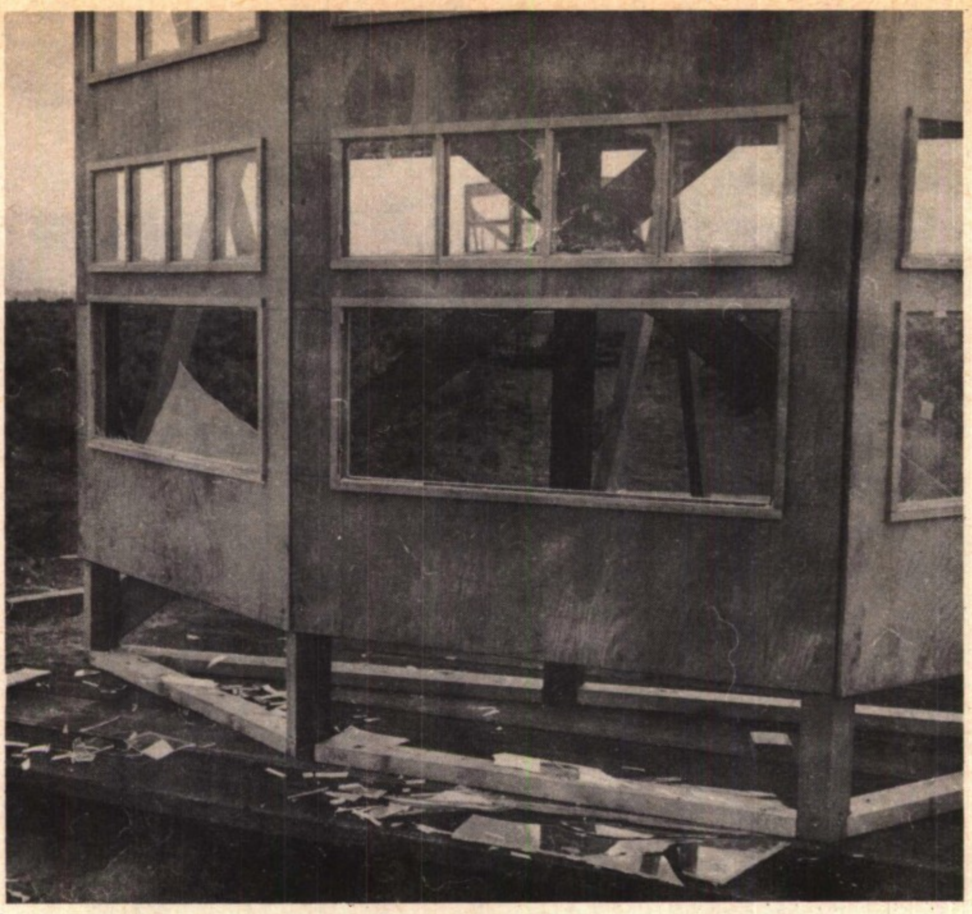


Figure 23. Glass breakage, glass test panel assembly No. 1, Test 1.

2. Test No. 1–A, fired at 0835, 10 Aug 46

A. Field Arrangement. Same as in Shot 1, this test repeating the latter in all respects except that the number of instruments was reduced and no glass test panels were set up.

B. Description of Explosion. In all appearances, closely similar to that of Shot 1.

C. Crater.— The crater was slightly smaller than in Shot 1 and the steep-sided deeper portion or "crater within a crater" did not occur, the sides sloping more uniformly from lip to bottom. For plan and profiles, see figure 25.

D. Earth Displacement. The permanent horizontal and vertical earth displacements are tabulated in table VII and plotted on the graph with the others, figures 69 and 70.

E. Damage to Target Igloo. The front wall was badly cracked and pulled away ⅛-inch from the arch at its top; however, the damage to the arch barrel was slight and was similar to that experienced in Shot 1. This target igloo had been used as the target in Shot 3, in which a crack had been started in the front end wall. See figure 26 for an illustration of these cracks. No other damage to this igloo occurred.

F. Displacement of Target Igloo. (1) Transient: The floor gage read ½-inch, the arch-floor gage ³⁄₁₆-inch.

(2) Permanent:

Transverse:	Front end moved ¼ inch toward explosion.	
	Rear end moved ⅜ inch toward explosion.	
Longitudinal:	No movement.	
Elevation:	Front end raised 0.5 inch.	
	Rear end raised 0.2 inch.	

There was no appreciable permanent change in the arch-to-floor distance.

TABLE VI

PEAK BLAST PRESSURES, P. S. I. GAGE, TEST 1

(a) Aberdeen Paper Blast Meters

Distances from charge (feet)	Meter lines					
	1	2	3	4	5	6
30	...	...	...	7.7–12.6	...	>12.6
38	7.7–12.6	...	7.7–12.6	...	7.7–12.6	...
50	5.8– 7.7	...	5.8– 7.7	7.7–12.6	7.7–12.6	5.8–7.7
64	3.6– 5.8	...	3.6– 5.8	...	5.8– 7.7	...
82	3.6– 5.8	3.6–5.8	3.6– 5.8	...	3.6– 5.8	...
106	2.7– 3.6	...	2.7– 3.6	2.7– 3.6	3.6– 5.8	2.7–3.6
135	2.7– 3.6	...	1.8– 2.7	...	3.6– 5.8	...
173	1.2– 1.8	...	.8– 1.2	...	2.7– 3.6	...
222	.8– 1.2	1.2–1.8	.8– 1.2	.8– 1.2	1.2– 1.8	.8–1.2
285	.6– .8	...	.6– .8	...	.6– .8	...
365	.4– .6	.4– .6	<.4	.4– .6	.4– .6	<.4
469	<.4	...	<.4	...	<.4	...

(b) Plywood Box Foil Meters

Distances from charge (feet)	Meter lines					
	1	2	3	4	5	6
30	14.7	16.8	9.4	12.5	20.0	16.8
38	11.5	...	9.4	...	12.5	...
50	7.25	...	5.6	7.25	7.25	7.25
64	4.4	...	4.4	...	7.25	...
82	3.3	3.3	3.3	...	4.4	...
106	<3.3	...	<3.3	3.3	3.3	<3.3
135	<3.3	...	<3.3	...	<3.3	...
173	<3.3	...	<3.3	...	<3.3	...
222	<3.3	<3.3	<3.3	<3.3	<3.3	<3.3

TABLE VII

AVERAGE PERMANENT EARTH DISPLACEMENT IN INCHES, SHOT 1–A

Distance from center of charge, feet.

	10	15	20	25	30
Vertical	+0.57	+0.66	+0.51	+0.36	+0.27
Horizontal	+1.47	+.12	0	0	0

+Means up and away from explosion.

TABLE VIII

PEAK BLAST PRESSURES, P. S. I. GAGE, TEST 1–A

Aberdeen Paper Blast Meters.

Distances from charge (feet)	Line 1	Line 5
30	7.7–12.6	>12.6
106	2.7– 3.6	3.6–5.8
285	.6– .8	.6– .8

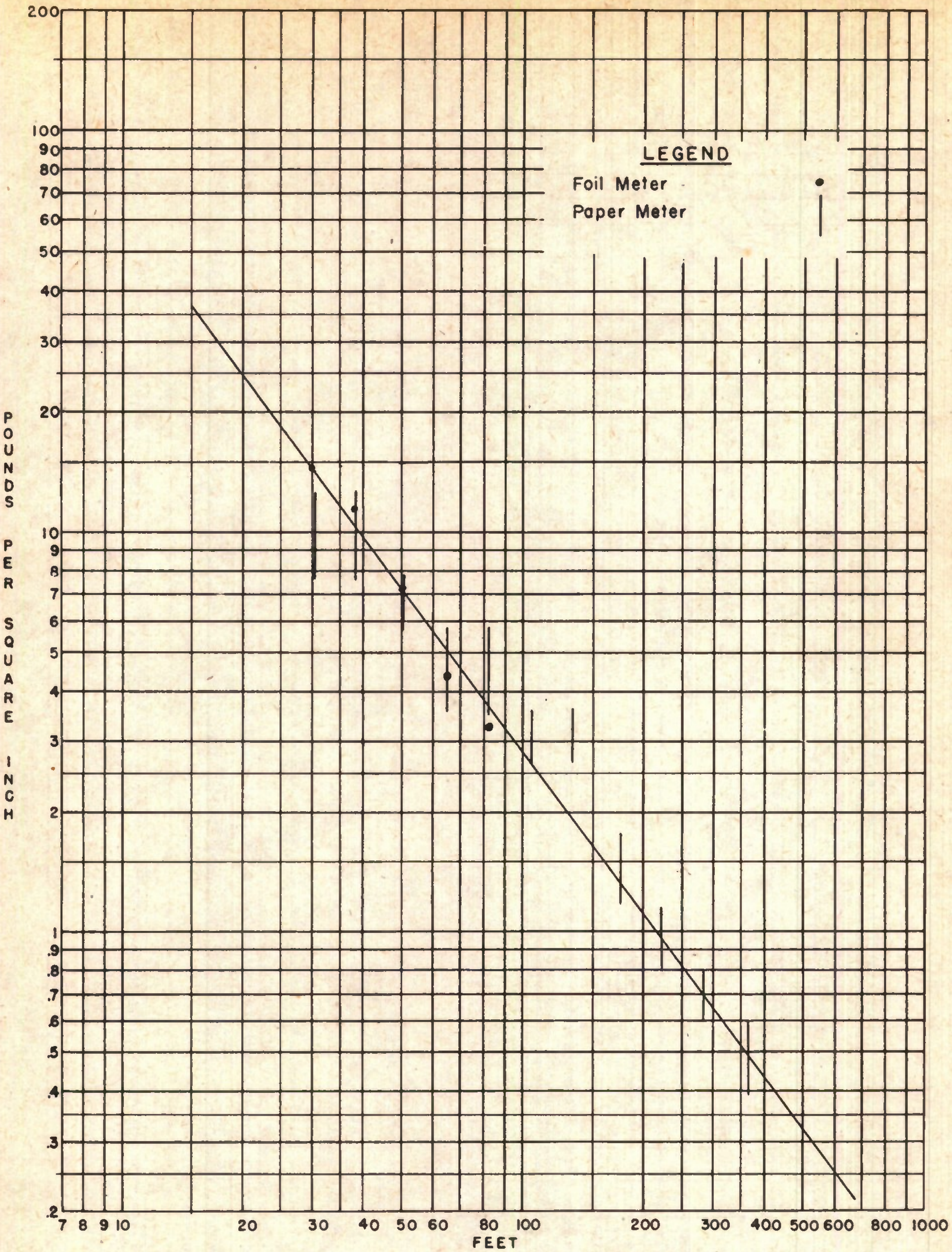


FIG.24A

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 1 & 1A Line No.1 (Off Front)

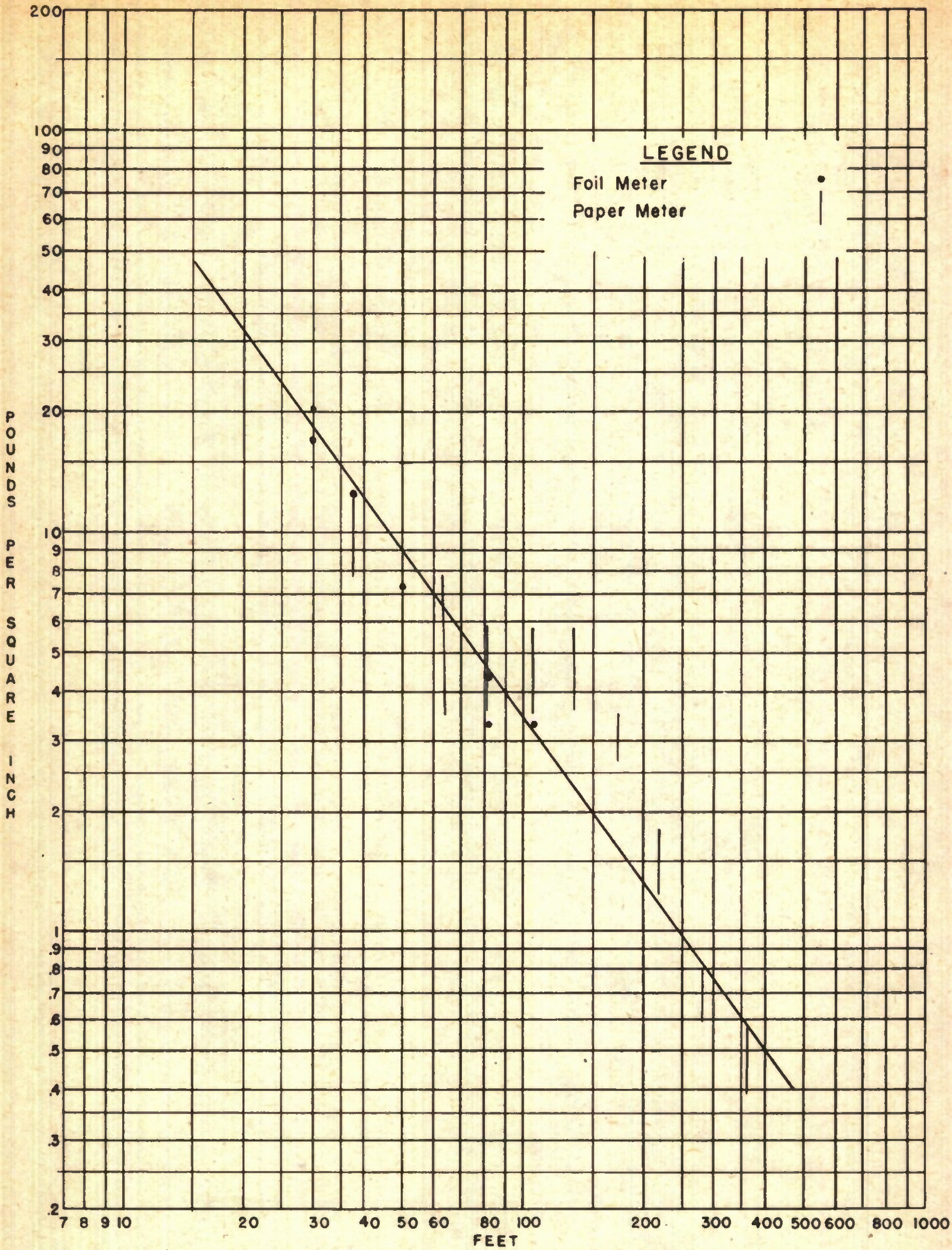


FIG. 24B

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 1 & 1A Lines No. 2 & 5 (Off Sides)

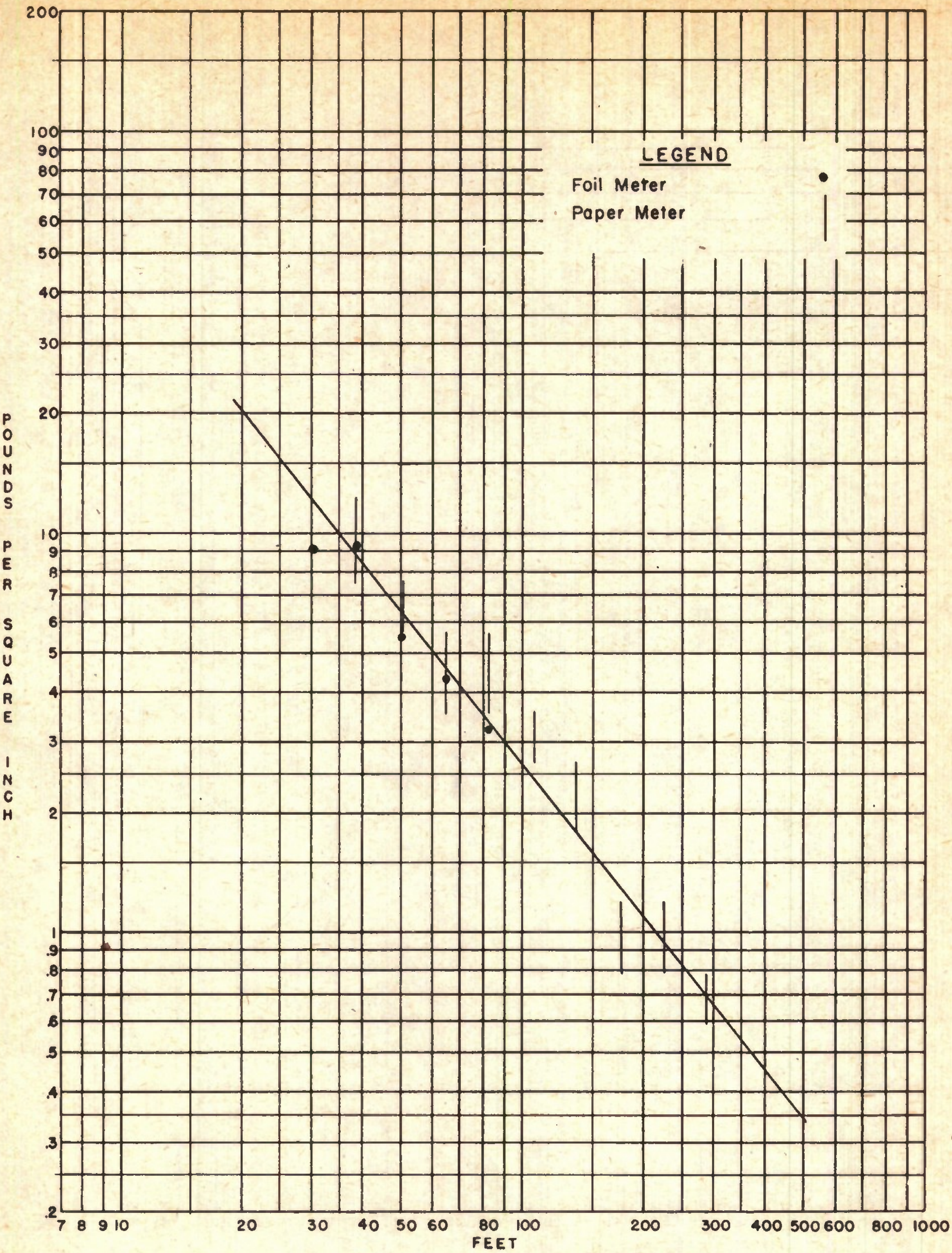


FIG.24C

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. I   Line No.3 (Off Rear)

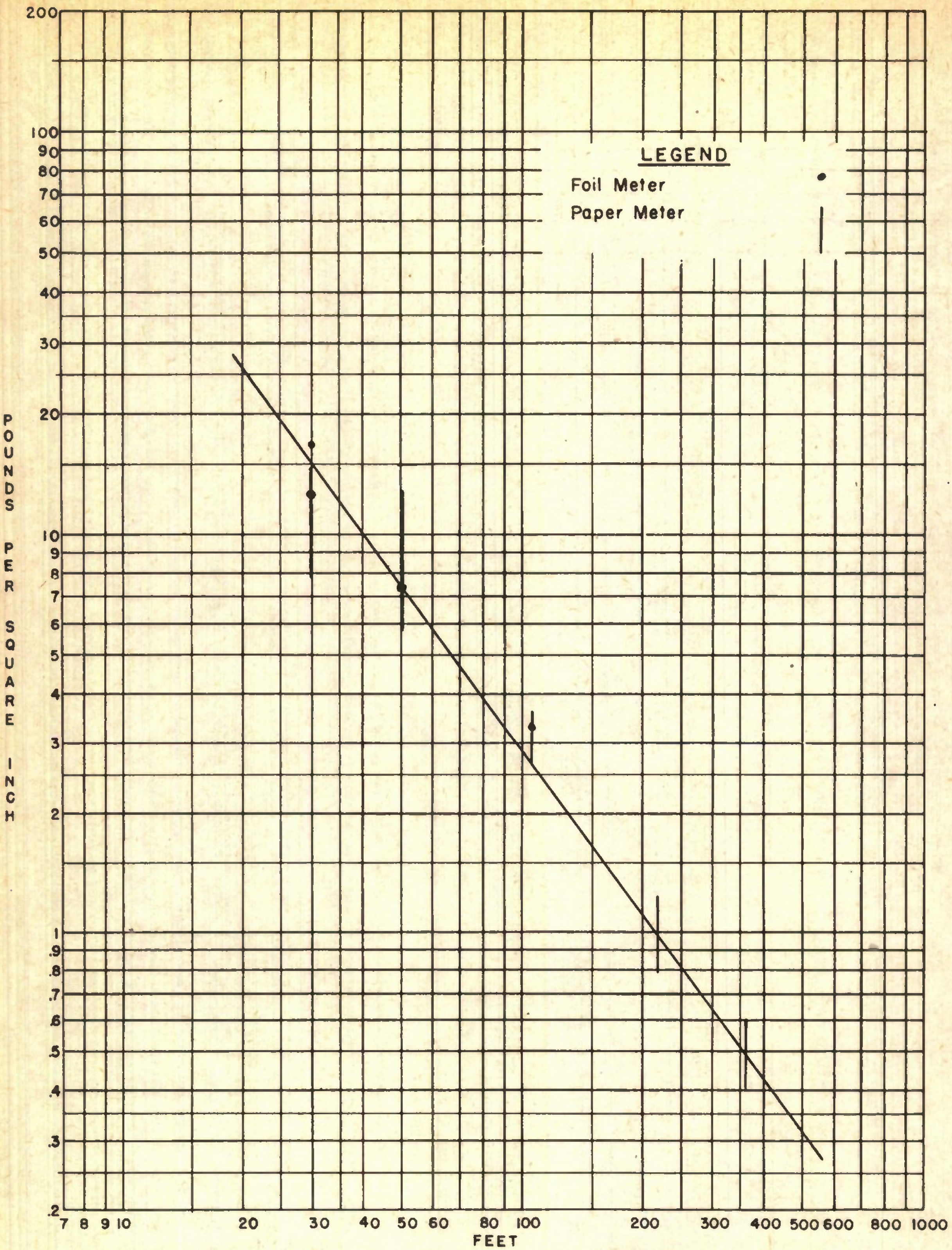
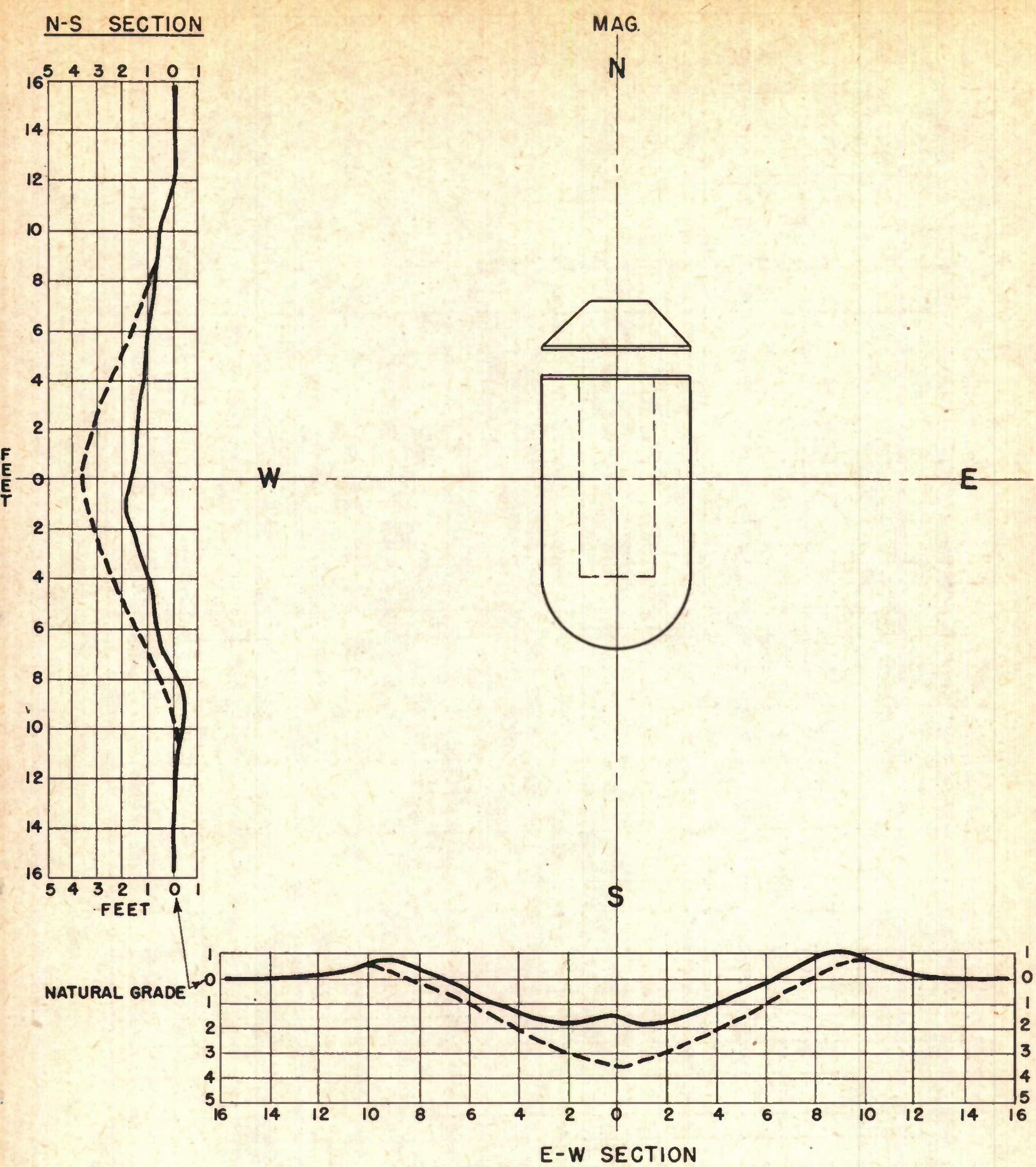


FIG.24D

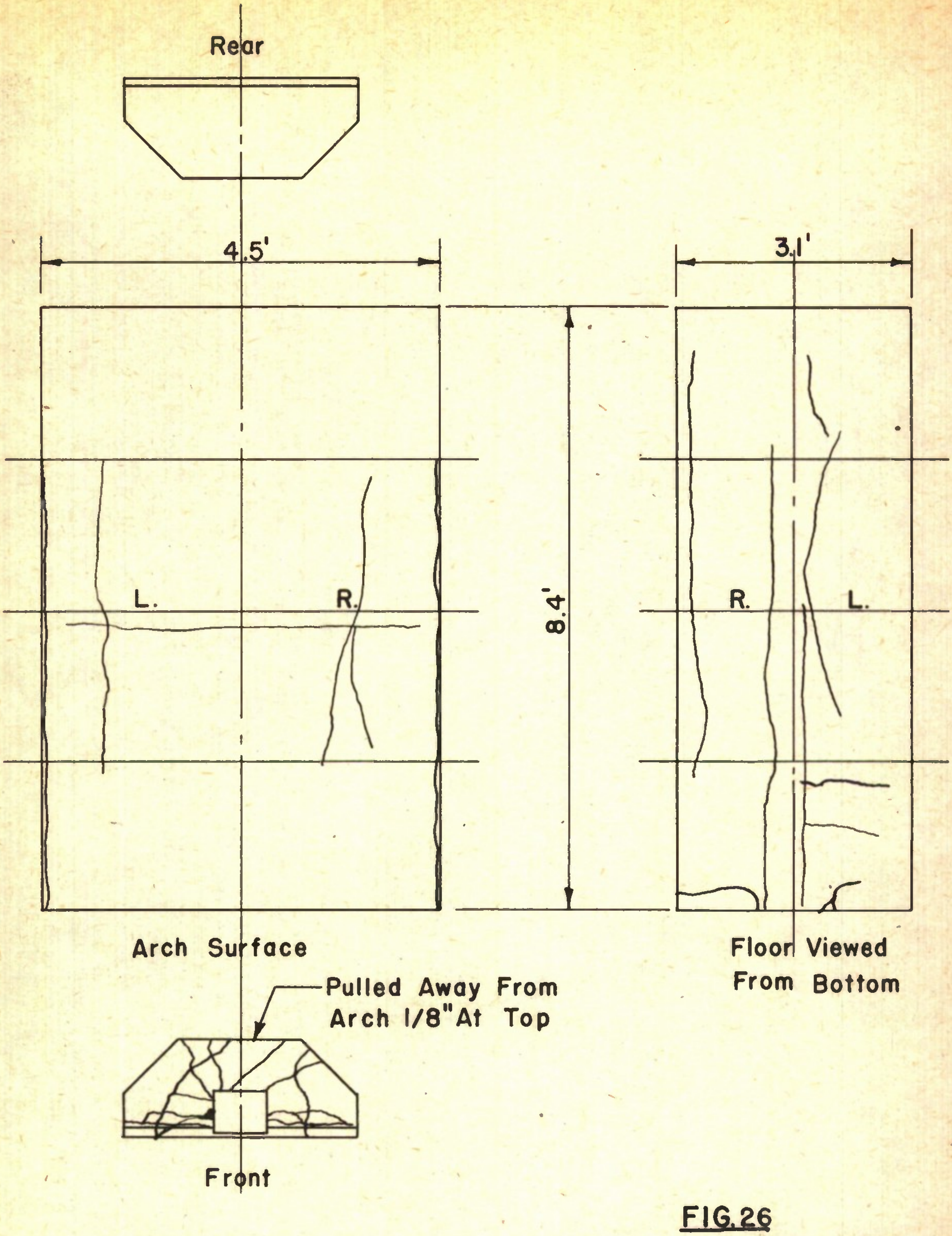
PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 1 Lines No. 4&6 (Off Quarters)



LEGEND
—— Apparent Crater
- - - Estimated True Crater

FIG. 25
CRATER PROFILES
Model Test No. 1A

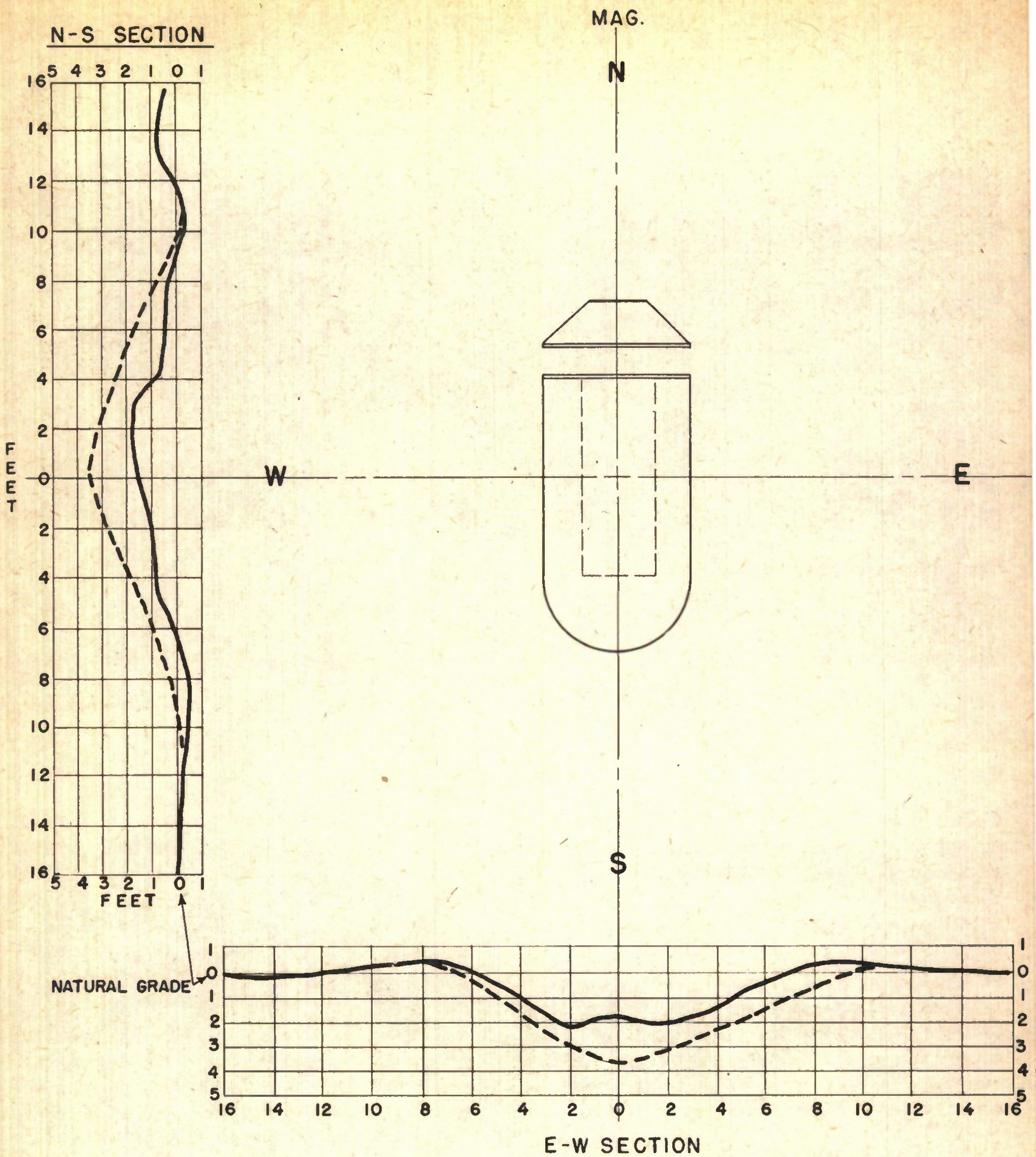


Shape I Earth Cover On Primary Igloo
Charge Weight 250 #

FIG. 26
DIAGRAM OF CRACKING
TARGET IGLOO
Model Test No. IA

Figure 27. Field arrangement, Test 2.

Figure 28. Crater, Test 2.



LEGEND

—— Apparent Crater

- - - Estimated True Crater

FIG. 29
CRATER PROFILES
Model Test No. 2

Figure 30. Target igloo after shot, Test 2.

G. Air Blast. Peak air blast pressure readings agreed well with those obtained in Shot 1. The values are tabulated in table VIII and plotted on figure 24 with those of Shot 1. A reading obtained with the "Arco" ball crusher gage gave a pressure of 48 p.s.i. at 12 feet.

H. Fragmentation. Demolition of the primary igloo was complete as in Shot 1, only a few pieces of the floor slab being found within the crater, several smaller pieces of concrete within 100 feet, and none beyond. Pieces of bangalore casing were widely scattered, as in Shot 1.

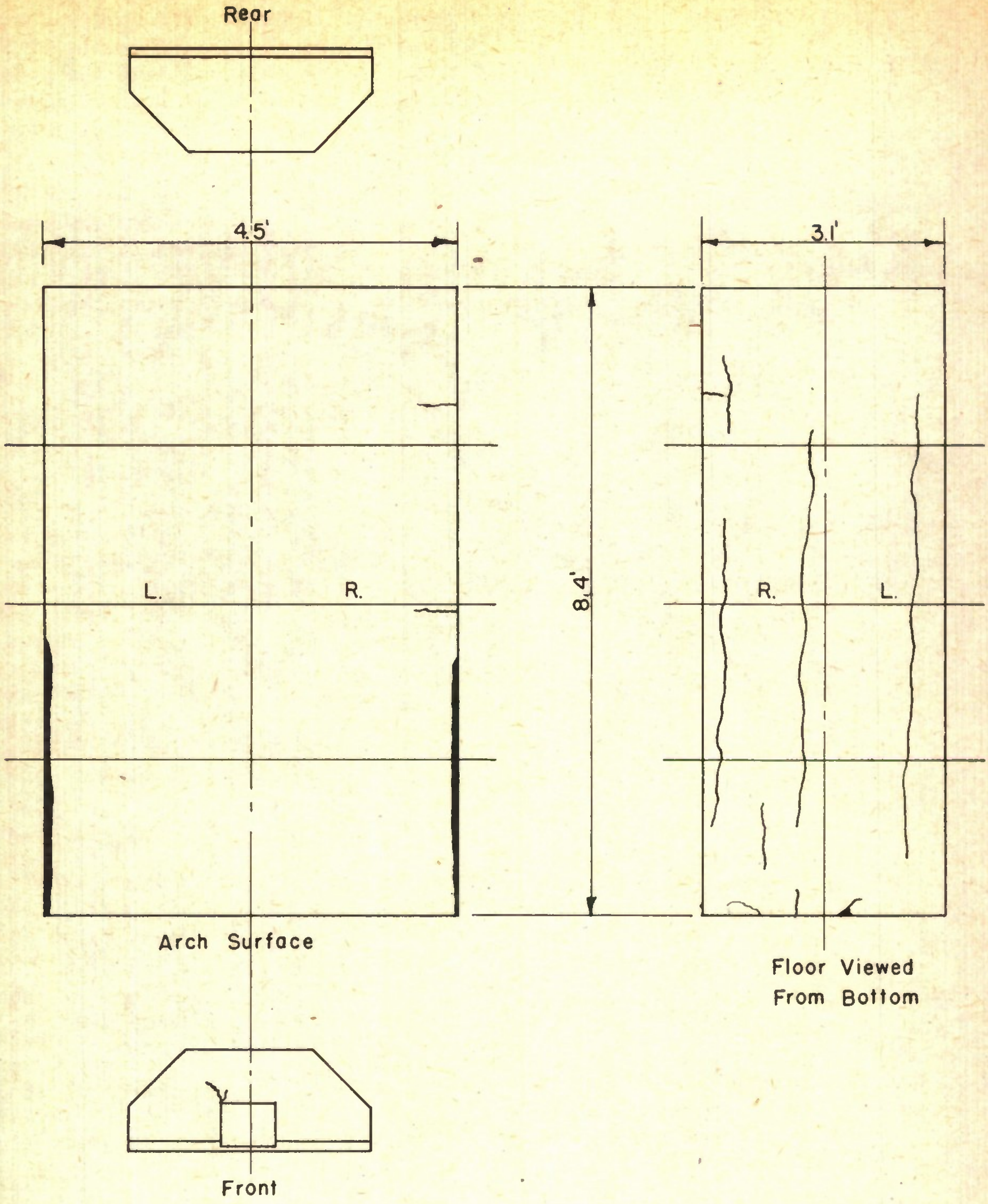
3. Test No. 2, fired at 1000, 1 August 1946

A. Field Arrangement. Primary and target igloos, as shown by figure 1, and illustrated in the photograph, figure 27. Standard earth cover on the target igloo, and Shape No. 2 from figure 9 on the primary igloo. Charge weight, 250 pounds amatol.

B. Description of Explosion. A high order detonation, with a bright flash and a brown smoke and dust cloud which seemed larger than in Test 1. The cloud hung in the air for some time, gradually diffusing and dissipating. There was no wind, and the sky was clear and cloudless. Difficulty was experienced in firing the charge as in the first test, and all but three caps were disconnected before the shot was actually detonated. The detonation was complete, however.

C. Crater. The diameter was 16.1 feet transversely to the igloo (east-west) and 12.0 feet longitudinally (north-south). Its apparent depth was 2.2 feet and it was 3.5 feet deep to sound bottom. The crater was not benched as in Shot 1, but graded nearly uniformly from lip to the deepest point. Figure 28 is a picture of this crater, and figure 29 shows its profiles.

D. Earth Displacement. Permanent horizontal and vertical earth displacements are tabulated in table IX and plotted on the graphs, figures 69 and 70. The displacements close to the explosion were much greater than they were in the first test.



Shape 2 Earth Cover On Primary Igloo
Charge Weight 250#

FIG. 31
DIAGRAM OF CRACKING
TARGET IGLOO
Model Test No. 2

TABLE IX

AVERAGE PERMANENT EARTH DISPLACEMENT IN INCHES, SHOT 2

Distance from center of charge, feet

	8	13	18	23
Vertical	+6.83	+0.47	+0.21	0
Horizontal	+11.11	+1.09	+.02	0

E. Damage to Target Igloo. Figure 30 is a photograph showing the appearance of the target igloo after the shot and prior to removal of the cover. Figure 31 is a sketch showing the cracking which occurred. The damage was generally less than in the first test, no cracks whatever appearing on the exterior or interior of the arch barrel. Inside the igloo along the junction of the arch and the floor slab on the near side, some loosening had occurred, which appeared to be a breaking and cracking of some of the mortar which had been applied as a rim or raised edge on the outside of the igloo on the projecting edge of the base slab, and had flowed through under the edge of the arch barrel, forming a film or crust weakly bonded to the floor slab and arch. There was no evidence of cracking along the outside edge, hence this mortar breaking is not considered damage to the igloo itself. The front end wall suffered a crack about 6 inches long running diagonally up to the left from the top left corner of the door as viewed from the outside. The floor slab was cracked in front of the doorway and suffered longitudinal cracks. The door was not damaged, but the ½-inch steel channel latch-bar was slightly bent. The earth cover was left uneven and rough, and some subsidence had occurred.

F. Displacement of Target Igloo. (1) Transient: The floor gage registered $\frac{5}{16}$ inch; the arch-floor gage $\frac{3}{32}$ inch. (2) Permanent: There was no apparent displacement, but accurate measurements were not obtained.

G. Glass Breakage. In test panel assembly No. 1 (215 feet), the highest large pane in the 90° panel evidently fell out toward the explosion without breaking and two corners were broken off on striking the platform. In No. 2 (287 feet), the lowest large 90° pane was broken and pulled in toward the explosion but most of the pane remained in the frame. No other glass breakage occurred, although there was considerably loosening and falling out of putty in the first two assemblies, and one instance of loosened putty in the farthest assembly (430 feet). See appendix A for a graphic record of the breakage.

H. Air Blast. Values of peak pressure obtained by Aberdeen paper meters and the aluminum foil gages are tabulated in table X and plotted on logarithmic paper in figure 32. The straight line best fitting this data indicates about 35 p. s. i. at 15 feet and 0.45 p. s. i. at 500 feet off the side of the primary igloo. A few credible readings were obtained from the NOL ball crusher gages in this test. All the readings are presented in the table.

I. Fragmentation. The only large pieces of concrete were found in and immediately around the crater. These were pieces of the floor slab, the largest being about 12 inches by 6 inches by 1½ inches. Most of these fragments were found in the south part of the crater, up near the edge. A few small (up to 2-inch) pieces of concrete from the arch or end walls were found within 150 feet. Most of the concrete was too finely fragmented to be recognized or found. The area within 250 to 300 feet was found to contain numerous small (2- to 3-inch) fragments of bangalore casing.

4. Test No. 3, Fired at 1020, 2 August 1946

A. Field Arrangement. Primary and target igloos, according to figure 1 and illustrated in the photograph, figure 33. The earth cover on the primary igloo was Shape No. 3 from figure 9 and on the target igloo it was standard. Charge weight, 250 pounds. The interior of the primary igloo was carefully inspected to determine whether the increased weight of earth cover, which was more than four times the normal amount, had caused cracking of the arch. No cracks or evidence of failure was observed, the structure apparently bearing the increased load with no ill effects.

B. Description of Explosion. A high order detonation, with a flash followed by a large brownish smoke and dust cloud which hung in the air for some time before diffusing. There was no wind and the sky was clear. This shot was fired with seven caps in series, according to plan.

C. Crater. The average diameter was 15.2 feet. The phenomenon of a bench or small deeper

TABLE X

PEAK BLAST PRESSURES, P. S. I. GAGE, TEST 2

(a) Aberdeen Paper Blast Meters

Distances from charge (feet)	Meter lines					
	1	2	3	4	5	6
30	....	....	....	7.7–12.6	....	7.7–12.6
38	7.7–12.6	....	7.7–12.6	....	5.8– 7.7	....
50	5.8– 7.7	....	3.6– 5.8	7.7–12.6	7.7–12.6	5.8– 7.7
64	5.8– 7.7	....	3.6– 5.8	....	3.6– 5.8	....
82	3.6– 5.8	5.8–7.7	2.7– 3.6	....	3.6– 5.8	....
106	1.8– 2.7	....	1.8– 2.7	2.7– 3.6	1.8– 2.7	2.7– 3.6
135	1.8– 2.7	....	1.8– 2.7	....	1.2– 1.8	....
173	1.2– 1.8	....	1.2– 1.8	....	.8– 1.2	....
222	.8– 1.2	1.2– 1.8	.8– 1.2	.8– 1.2	1.2– 1.8	.8– 1.2
285	.6– .8	....	.6– .8	....	.6– .8	....
365	.4– .6	<.4	<.4	<.4	<.4	<.4
469	<.4	....	....	....	<.4	....

(b) Plywood Box Foil Meters

Distances from charge (feet)	Meter lines			
	1	3	5	6
30	16.5	7.25	11.5	11.5
38	11.5	5.6	9.4	....
50	5.6	4.4	5.6	5.6
64	4.4	4.4	4.4	....
82	3.3	<3.3	3.3	....
106	<3.3	....	<3.3	....

crater within a crater was again apparent as in Shot 1. The apparent depth was 2.4 feet and the true depth 4.3 feet. The crater is pictured in figures 34 and 35.

D. Earth Displacement. The data are presented in table XI and plotted in figures 69 and 70. The displacements of points close in to the explosion were much greater than in the first test.

E. Damage to Target Igloo. Figure 36 is a photograph showing the appearance of the target igloo after the explosion and prior to removal of the earth cover. Figure 37 is a sketch of the cracking which occurred. As may be seen, there was no cracking or other evidence of damage to the arch barrel or to the junction of the barrel with the base slab. The front end wall sustained one fine crack in the right half, running from the right-hand vertical edge 6 inches above the floor diagonally up to the left, about 6 inches in length. Two small cracks appeared in the floor, running from the front edge through the door, and ending 6 inches inside the igloo. The ½-inch channel latchbar was bent somewhat. No other damage was apparent.

F. Displacement of Target Igloo. (1) Transient:

Table X (continued)

Peak Blast Pressures, P. S. I. Gage, Test 2

(c) Ball Crusher Gages.

Meter line	Distances from charge-feet	Deformation, in. X 10^6	Calibration, in. X 10^6 /lb./in.^{2}	Pressure, lb./in.^{2}
1	7	0	28.8	....
1	12	2,400	30.2	79.5
1	15	100	30.6	....
1	15	1,800	30.6	58.8
2	7	0	28.8	....
2	10	200	29.8	....
2	10	1,800	29.8	60.4
2	12	200	30.2	....
2	12	100	30.2	....
2	18	200	30.9	....
2	18	200	30.9	....
3	7	1,800	28.8	62.5
3	12	3,700	30.2	122.5
3	15	1,100	30.6	35.9
3	15	100	30.6	....
4	12	0	30.2	....
4	12	6,300	30.2	208.5
5	7	4,400	28.8	153
5	12	0	30.2	....
5	15	100	30.6	....
5	15	200	30.6	....
6	12	400	30.2	....
6	12	1,300	30.2	43.0

The floor gage registered a rise of ⅜-inch; the arch-floor gage a decrease in inside crown height of ⅛-inch.

(2) Permanent: Transverse: North end moved ¼ inch away; South end ⅛ inch away.
Longitudinal: No movement.
Elevation: Both ends raised 0.2 inch.

G. Glass Breakage. Only one pane broke, that being the lowest large 90° pane in test panel

TABLE XI

AVERAGE PERMANENT EARTH DISPLACEMENT IN INCHES, SHOT 3

Distance from center of charge, feet.

	8	13	18	23
Vertical	+6.60	+1.30	+0.48	+0.12
Horizontal	+15.19	+1.33	+.03	0

+means up and away from the explosion.

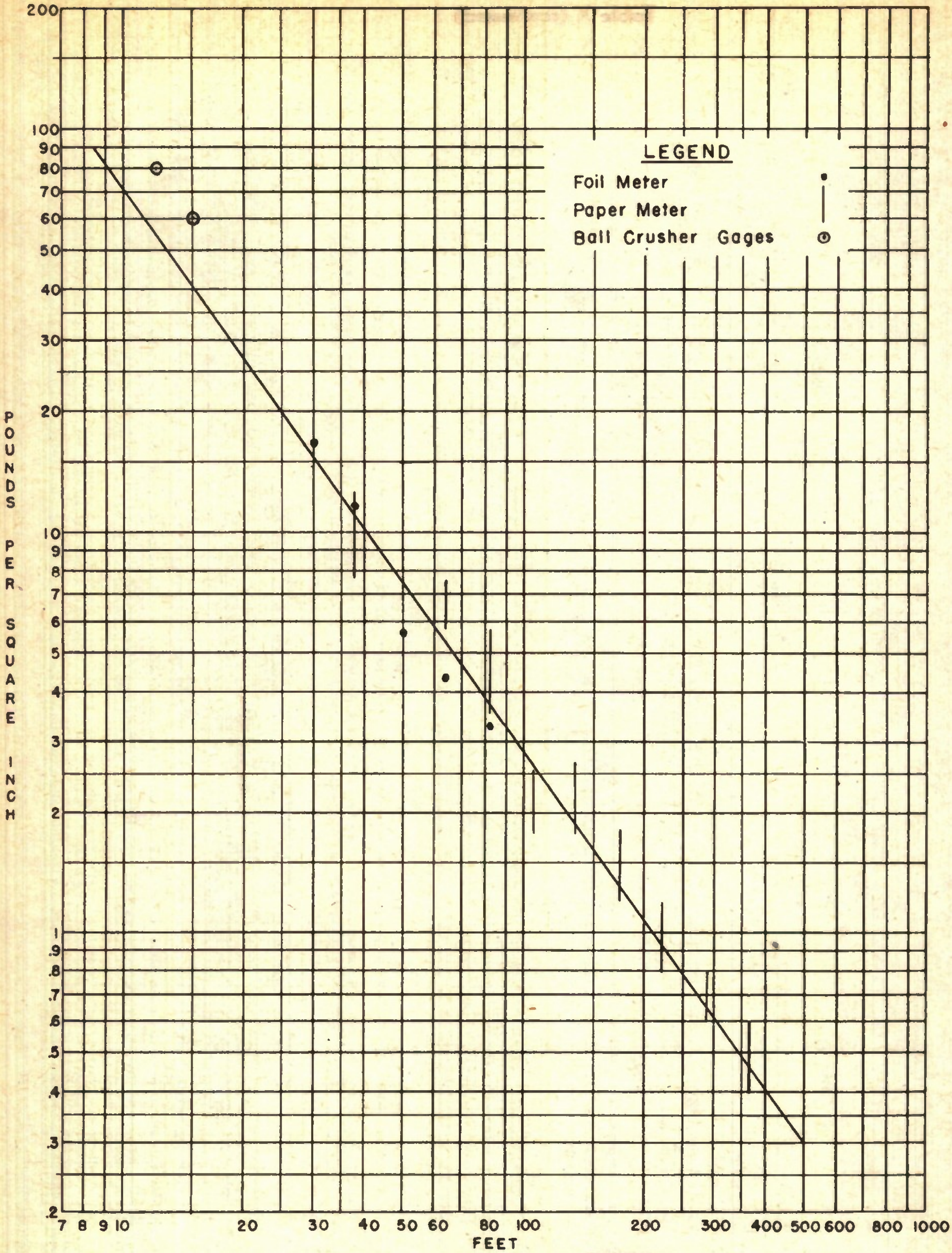


FIG.32A

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No.2 Line No.1(Off Front)

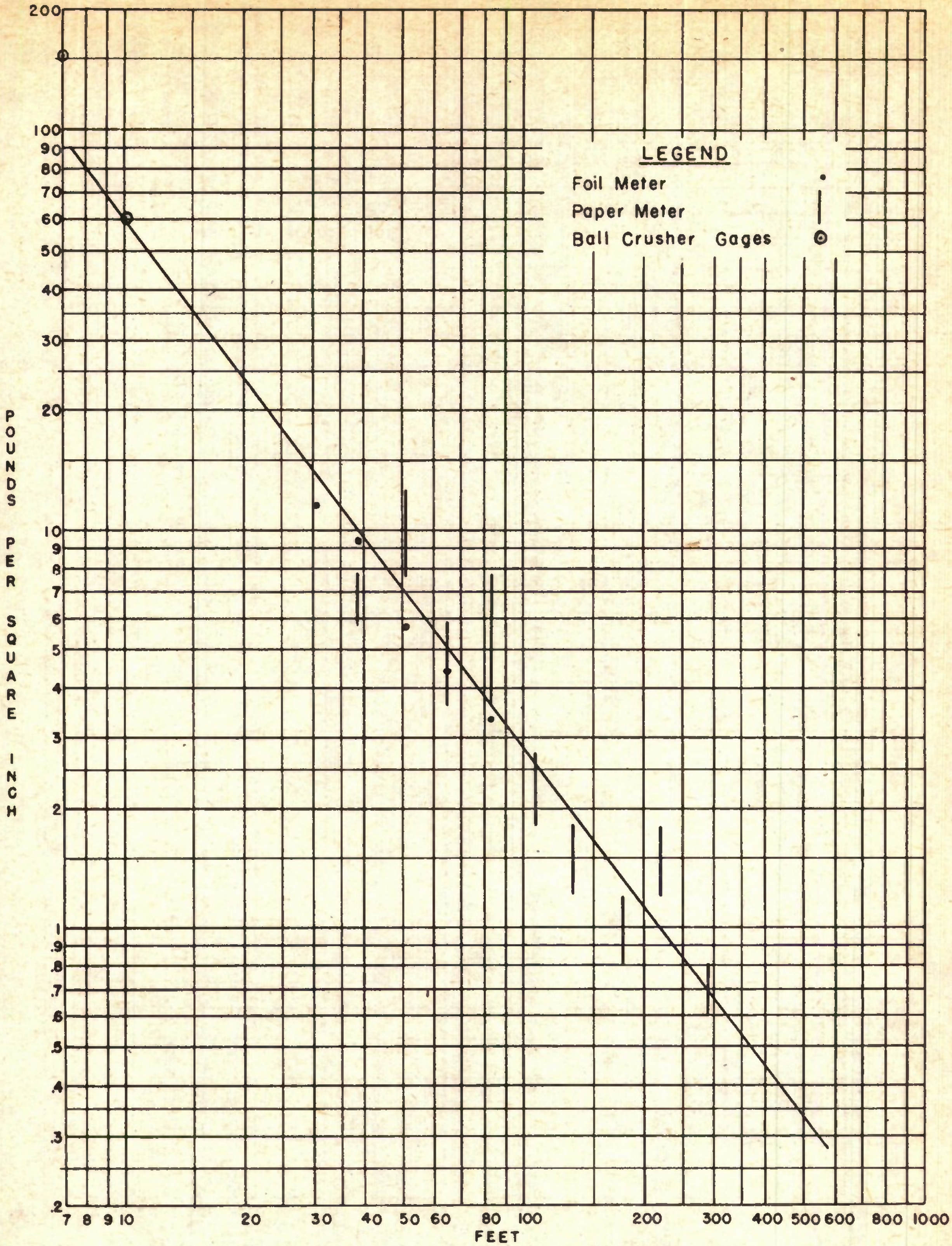


FIG.32B

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 2 Lines No. 2&5 (Off Sides)

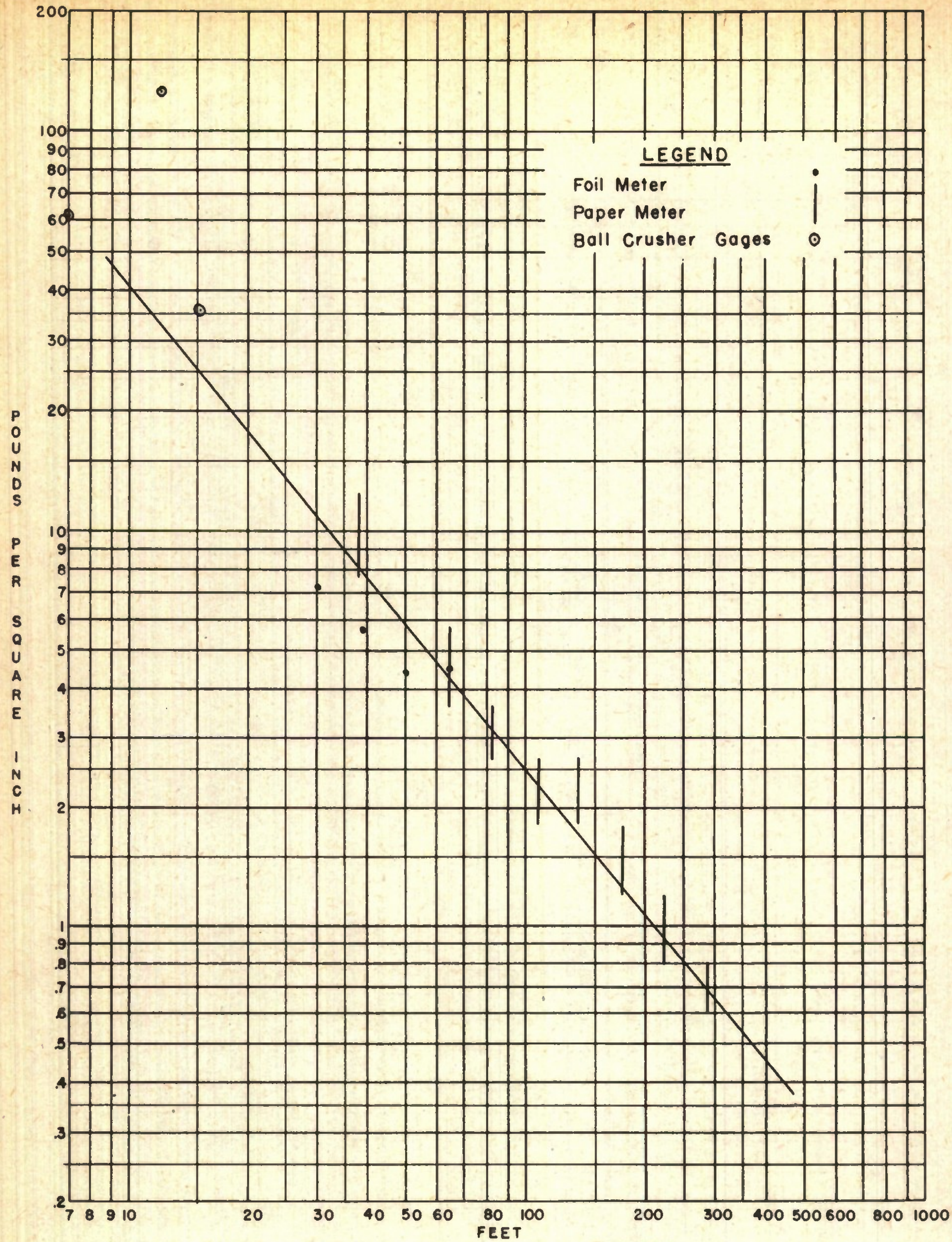


FIG.32C

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 2 Line No.3(Off Rear)

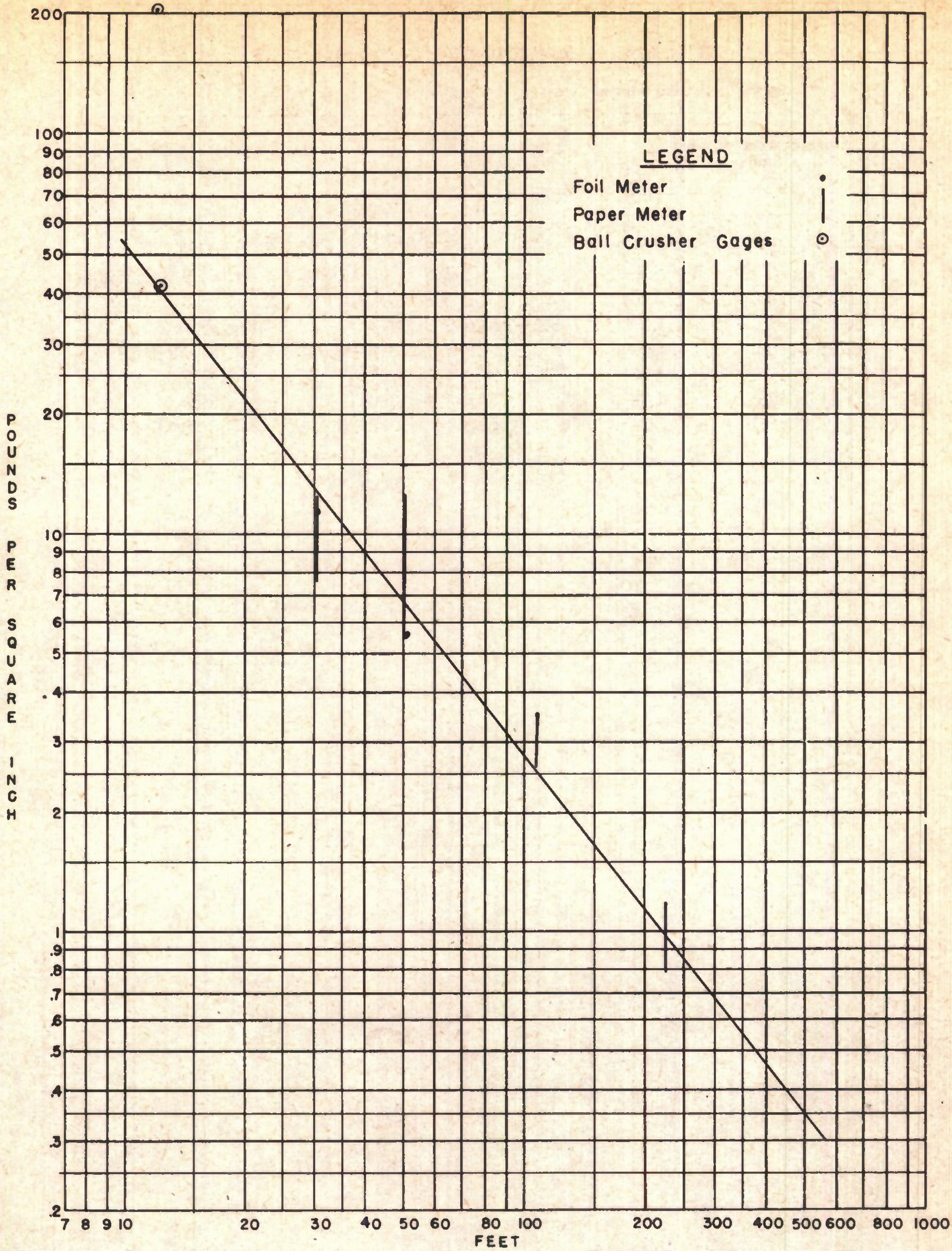


FIG.32D

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 2 Lines No.4&6 (Off Quarters)

TABLE XII

PEAK BLAST PRESSURES, P. S. I. GAGE, TEST 3

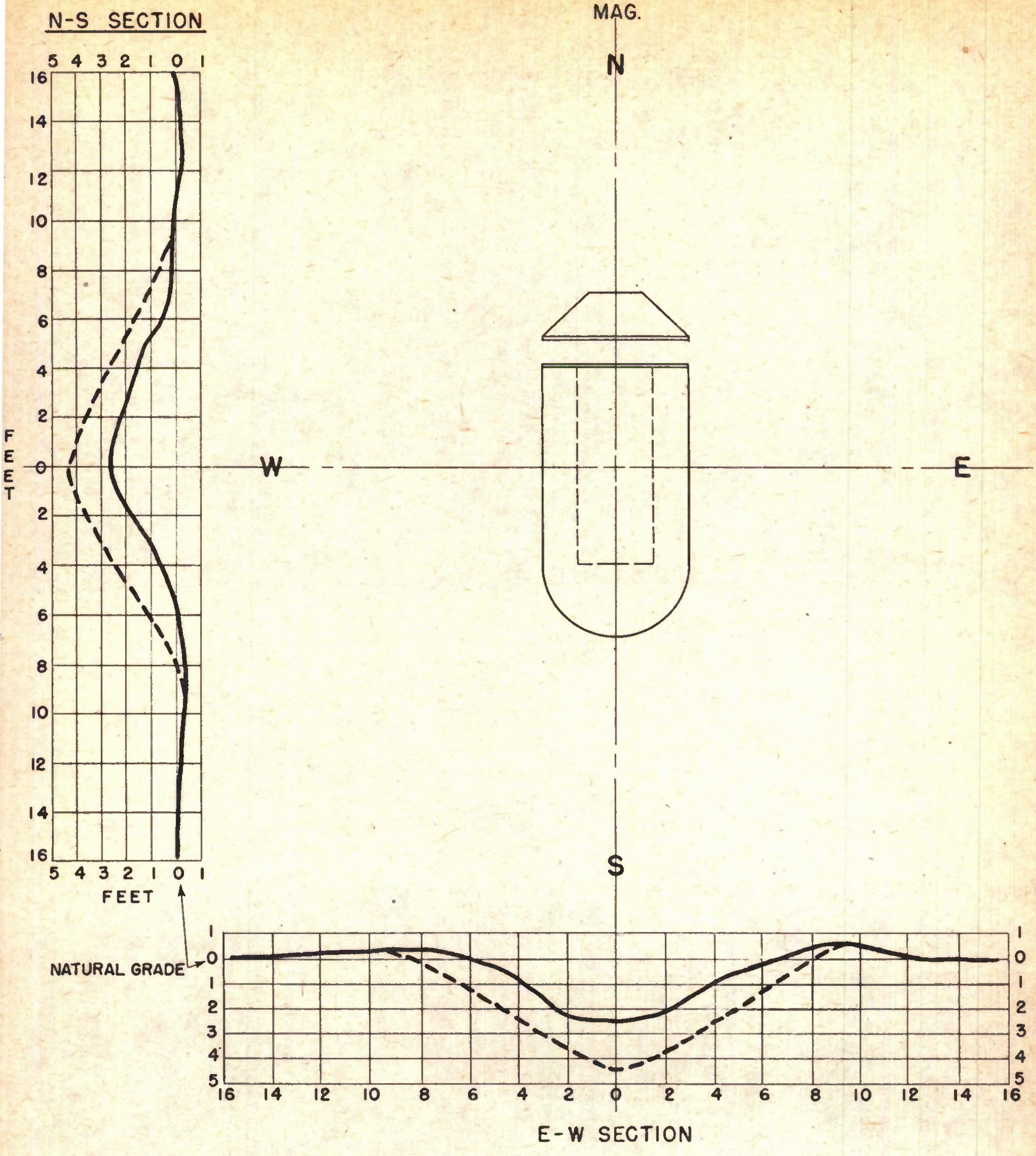
(a) Aberdeen Paper Blast Meters

Distance from charge (feet)	Meter lines					
	1	2	3	4	5	6
30	....	....	....	7.7–12.6	....	7.7–12.6
38	7.7–12.6	....	3.6–5.8	....	5.8–7.7	....
50	5.8– 7.7	....	3.6–5.8	3.6– 5.8	3.6–5.8	3.6– 5.8
64	3.6– 5.8	....	3.6–5.8	....	2.7–3.6	....
82	2.7– 3.6	2.7–3.6	3.6–5.8	....	1.8–2.7	....
106	2.7– 3.6	....	1.8–2.7	1.8– 2.7	1.2–1.8	2.7– 3.6
135	1.8– 2.7	....	1.2–1.8	....	.8–1.2	....
173	1.2– 1.8	....	.8–1.2	....	1.2–1.8	....
222	.8– 1.2	<.4	.8–1.2	.8– 1.2	.6– .8	.8– 1.2
285	.4– .6	....	<.4	....	<.4	....
365	<.4	<.4	<.4	<.4	<.4	<.4
469	<.4	....	<.4	....	<.4	....

(b) Plywood Box Foil Meters

Distance from charge (feet)	Meter lines			
	1	3	5	6
30	12.5	3.3	9.4	9.4
38	7.25	4.4	5.6	....
50	5.6	4.4	3.3	4.4
64	4.4	<3.3	3.3	....
82	<3.3	<3.3	3.3	....
106	<3.3	....	<3.3	....

Figure 33. Field Arrangement, Test 3.



LEGEND

— Apparent Crater

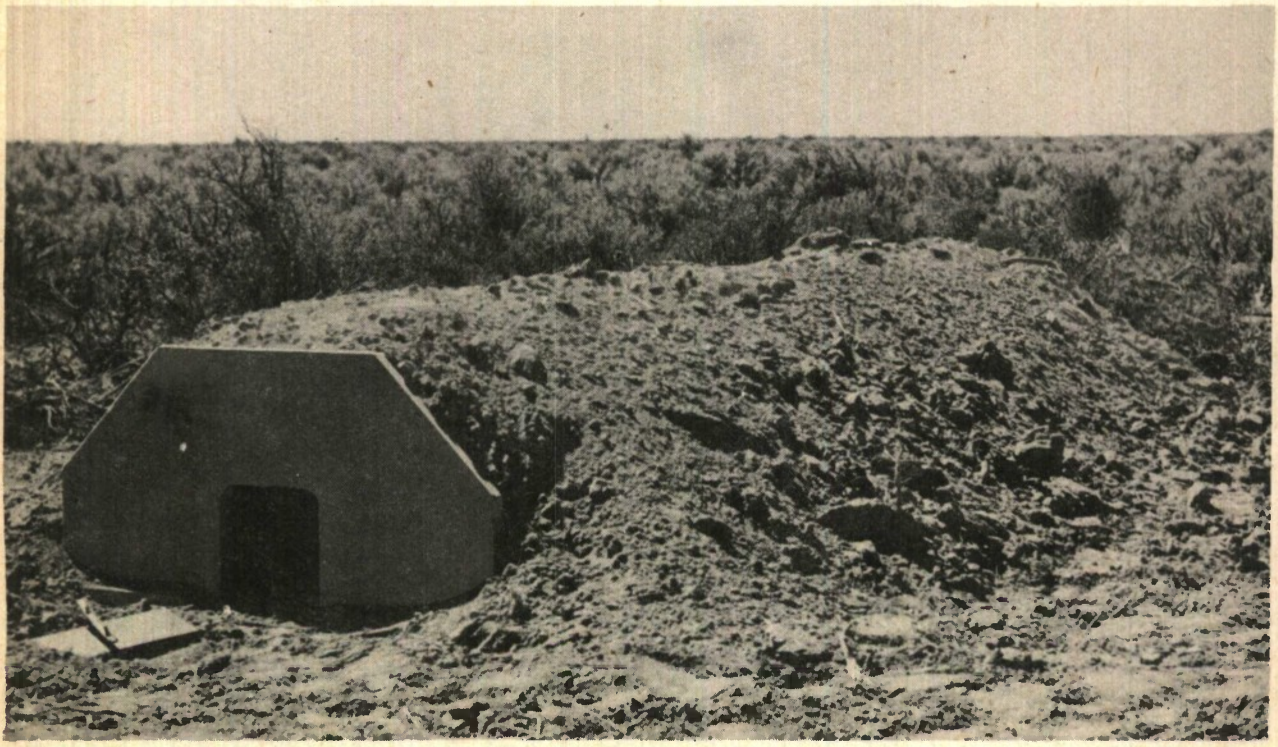
--- Estimated True Crater

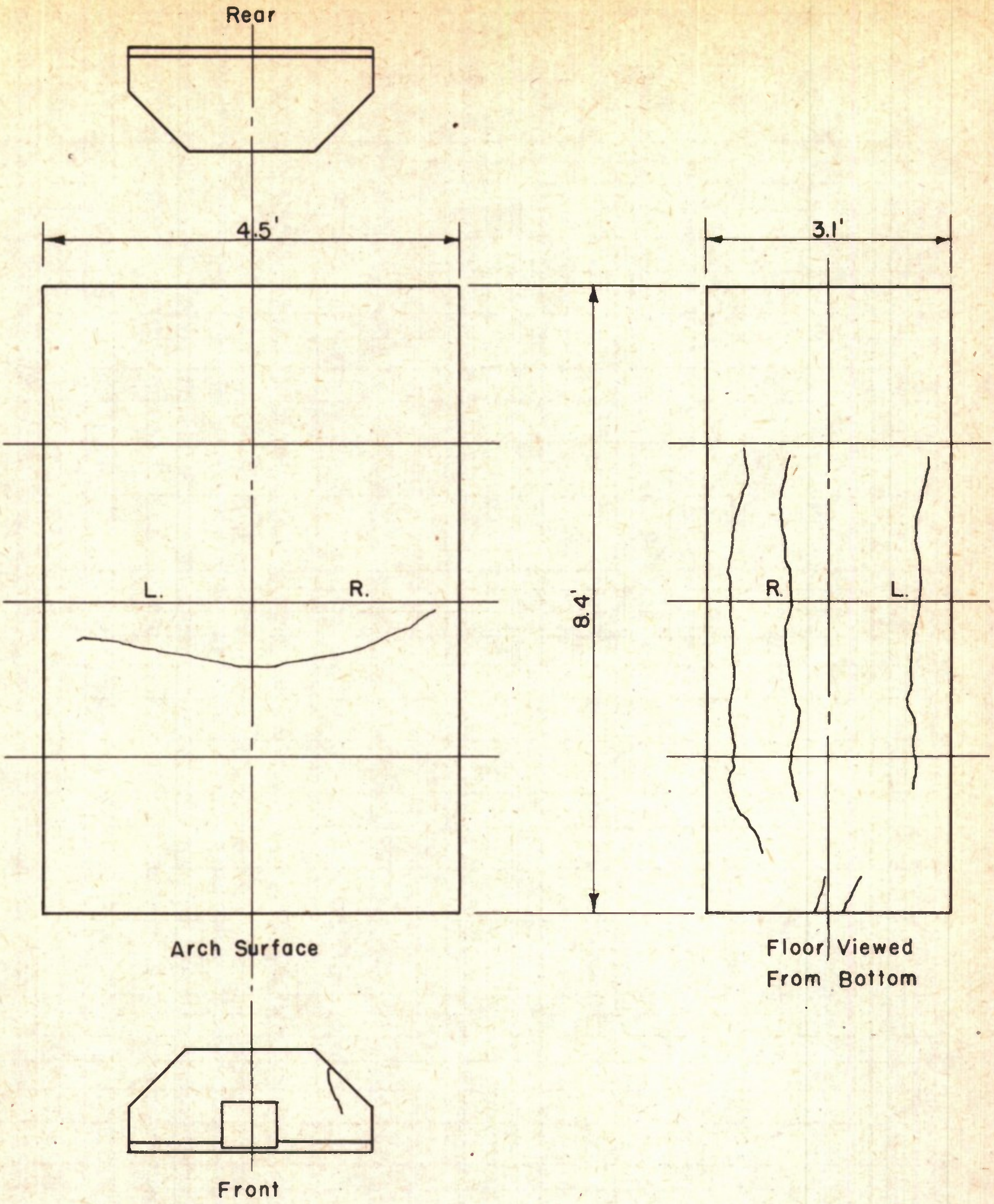
FIG. 34
CRATER PROFILES
Model Test No. 3

738942 O - 47 - 4

Figure 35. Crater, Test 3.

Figure 36. Target igloo after shot, Test 3.





Shape 3 Earth Cover On Primary Igloo
Charge Weight 250#

FIG.37
DIAGRAM OF CRACKING
TARGET IGLOO
Model Test No.3

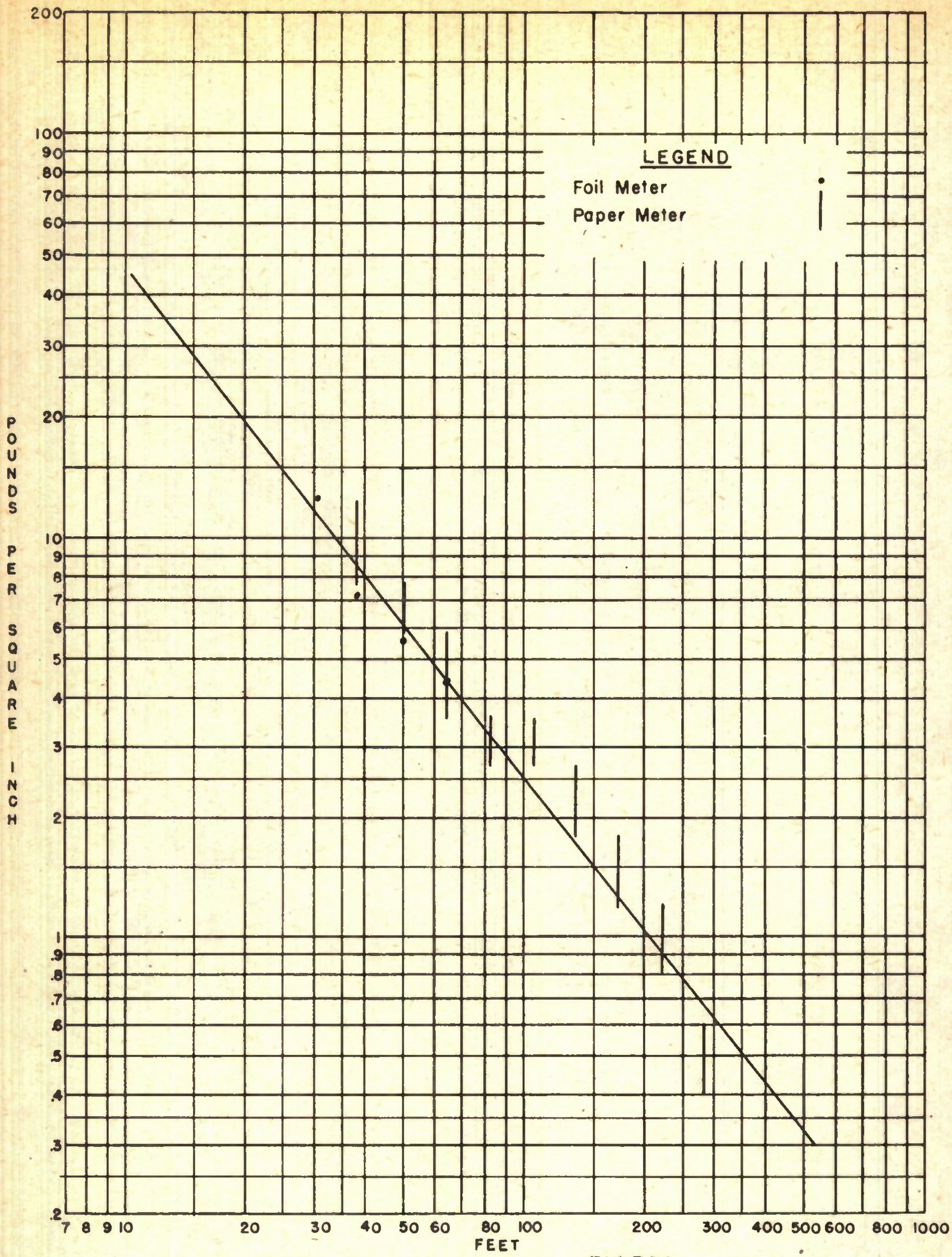


FIG.38A

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 3 Line No. 1 (Off Front)

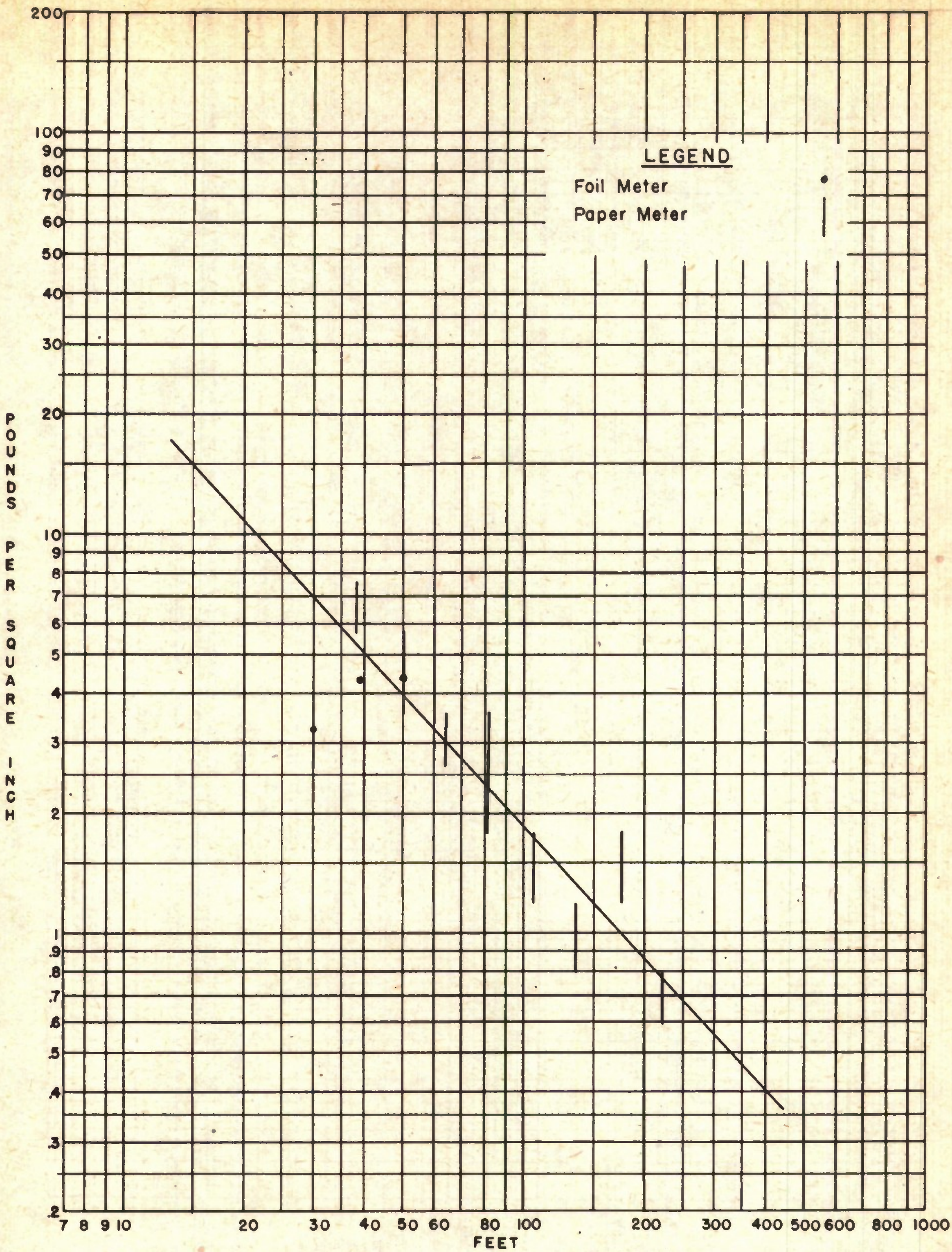


FIG.38B

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 3 Lines No. 2&5 (Off Sides)

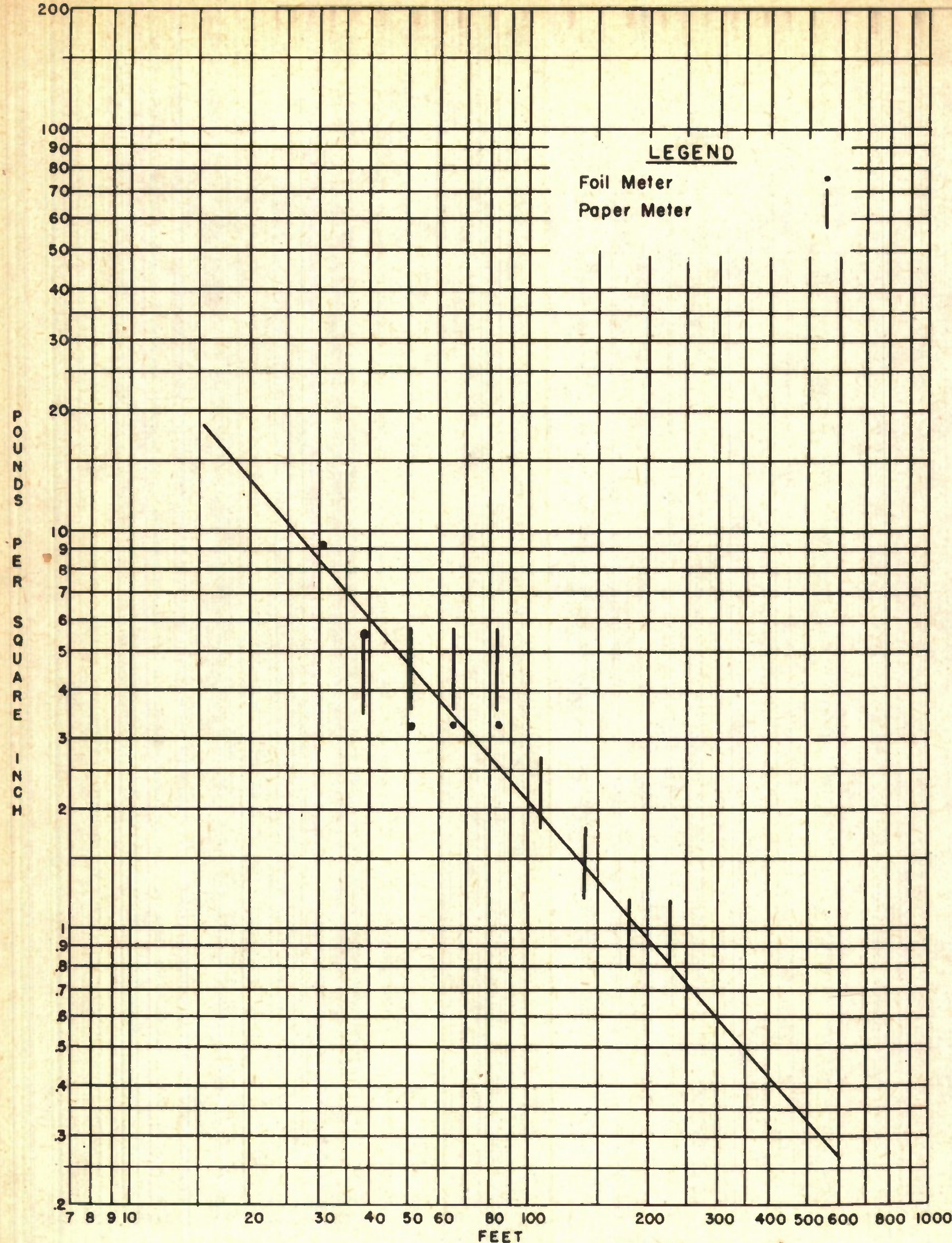


FIG.38C

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 3 Line No.3 (Off Rear)

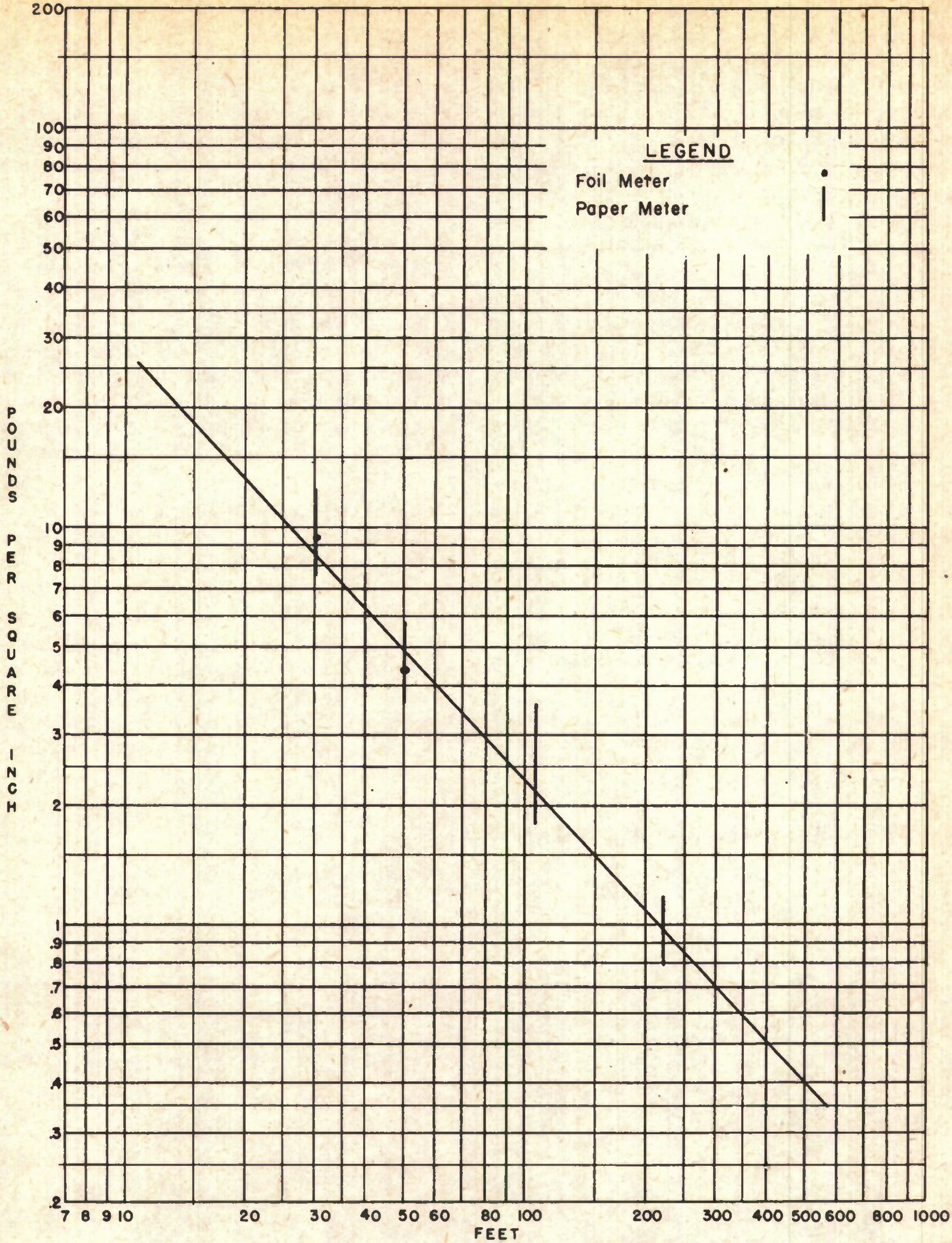


FIG.38D

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No.3 Line No.4&6(Off Quarters)

assembly No. 1 (215 feet). As in the previous shots, the pane fell out toward the explosion. Putty was loosened to some extent in the lower sections of assemblies No. 1 and No. 2. There was no noticeable effect on No. 3. See appendix A for the damage record sheet.

H. Air Blast. In this test the paper meters and the foil gages were consistent in indicating a decrease in peak blast pressures from those obtained in Test 1. The pressure-distance curve, figure 38, indicates about 15 p. s. i. at 15 feet and 0.4 p. s. i. at 400 feet off the side of the primary igloo. A difference also appears between the pressures along meter line 1 (directly out from the front of the igloo) and those along the other meter lines. The pressure values are presented in table XII. Ball crusher gages were not used in this test.

I. Fragmentation. The general character and distribution of fragments was the same as in the previous tests.

5. Test No. 4, Fired at 1030, 5 August 1946

A. Field Arrangement. Primary and target igloos, according to figure 2 and illustrated in the photograph, figure 39. Both igloos had standard earth cover. Charge weight, 500 pounds amatol.

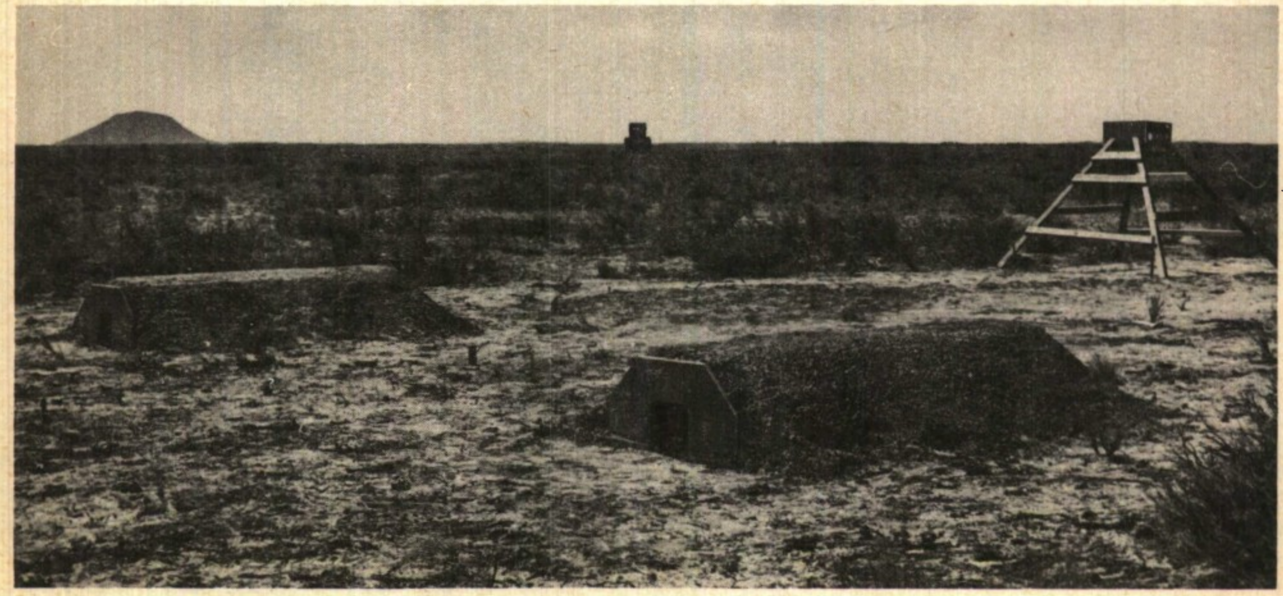
B. Description of Explosion. A high order detonation, showing a brilliant yellowish-white flash followed by large smoke and dust cloud, light brown to dark grey in color. No ground shock was felt at the shelter, 600 feet away. The sharp loud report and air shock wave arrived a brief instant after the flash. The shock was moderate but felt stronger than in the previous shots. The smoke and dust cloud, which appeared larger than in the 250-pound tests, dissipated rapidly to the northeast, as there was a 10 m. p. h. wind blowing from the southwest. The sky was clear. This shot was fired with 14 caps in series, distributed at random among the 56 bangalore torpedoes.

C. Crater. The diameter was nearly equal in all directions, and was 20.4 feet. This crater had steep sides and a nearly flat bottom, being shaped like a pie tin. It was 2.1 feet deep at its center (apparent depth). The true depth was 3.2 feet. See profiles, figure 40 and photograph, figure 41.

D. Earth Displacement. The values of permanent horizontal and vertical earth displacement at various distances from the center of the crater are given in table XIII, and plotted on the graphs, figures 69 and 70.

E. Damage to Target Igloo. The earth cover was very disheveled. The front end wall was blown completely off the arch barrel, and was found badly cracked and lying face down 2½ feet in front of the igloo. This is illustrated by the photographs,

Figure 39. Field arrangement, Test 4. Primary igloo at left.



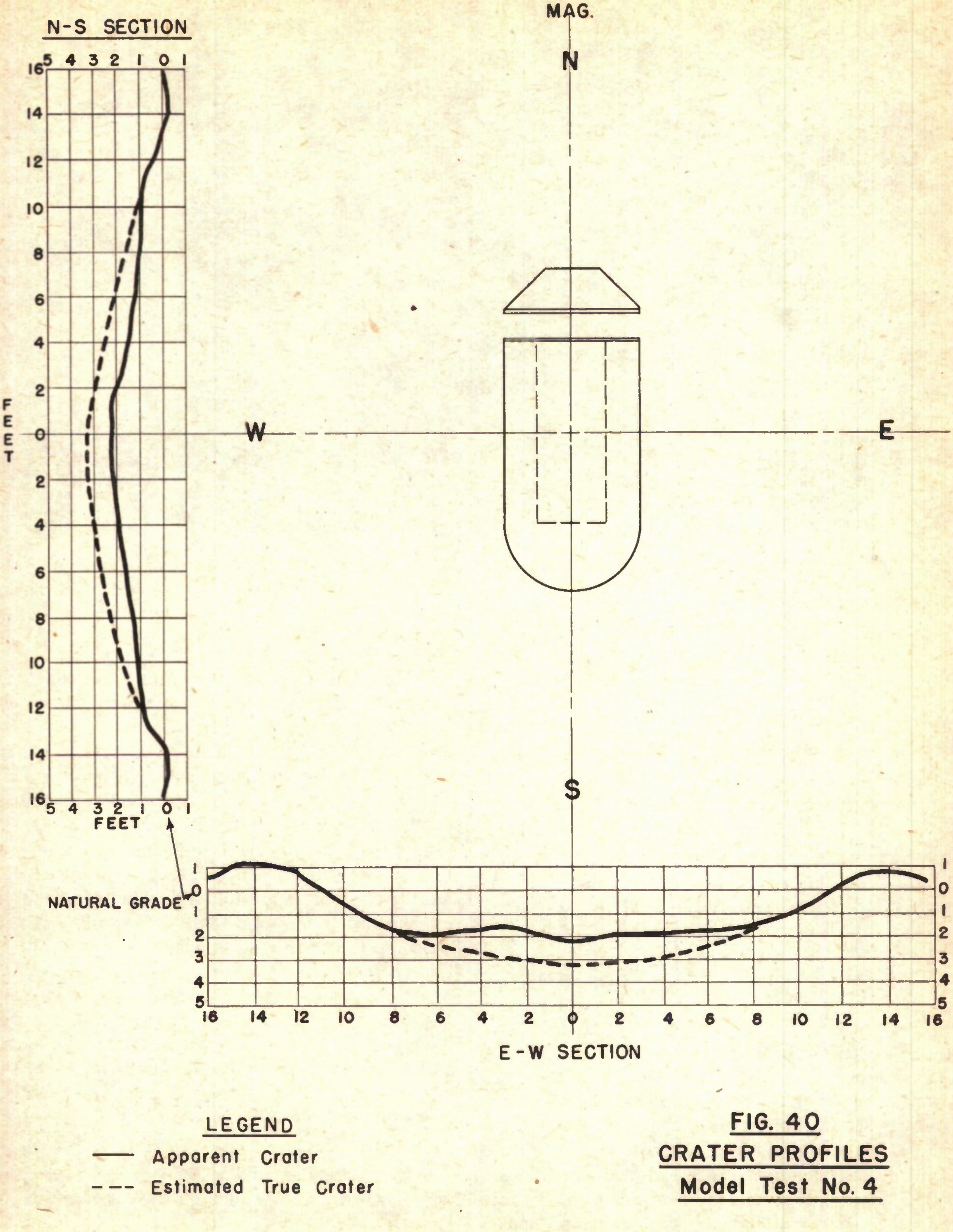


FIG. 40
CRATER PROFILES
Model Test No. 4

Figure 41. Crater, Test 4.

TABLE XIII

AVERAGE PERMANENT EARTH DISPLACEMENT IN INCHES, SHOT 4

Distance from center of charge, feet.

	13	18	23	28
Vertical.....	+3.40	+1.50	+0.48	+0.32
Horizontal...	+3.44	+.90	+.58	+.10

+means up and away from the explosion.

figures 42 and 43. The door was found underneath the end wall, the latchbar badly bent. The wire reinforcement which had passed from the arch into the end wall was pulled out of the end section and was left protruding from the arch. The barrel was cracked away from the floor slab from the front all the way to the rear end wall on the near side, and the junction was also broken on the far side to a point a little beyond half-way back. See the photograph of the interior of the igloo taken through the broken front end, figure 44. A network of cracks appeared on the near side of arch barrel, extending 7 feet back from the front and from 4 to 12 inches above the floor slab. This network consisted of three main longitudinal cracks interconnected by frequent diagonals. A central longitudinal crack appeared at the crown, extending nearly the entire length of the barrel, and two other longitudinal cracks appeared at approximately one-third and two-thirds the distance up the arch, respectively, on the far side of the barrel. The floor slab sustained a network of severe cracks. The cracking is illustrated by the sketch, figure 45. The rear end wall was not damaged. The dummy charge in this igloo was badly jostled, practically all the channels on the upper layer having been overturned and the aisle space was filled with fallen channels.

F. Displacement of Target Igloo. (1) Transient: The floor gage indicated a rise of $\frac{5}{16}$ inch; the arch-floor gage a decrease in arch-to-floor distance of $\frac{5}{16}$ inch also.

Figure 42. Target igloo after shot, Test 4.

Figure 43. Front end of target igloo after shot, Test 4, showing broken front end wall lying on ground 2½ feet in front of igloo, after being uncovered.

(2) Permanent:	Transverse:	Front end moved 1⅛ inches away; rear end moved ⅜ inch away.
	Longitudinal:	No movement.
	Elevation:	Front raised 0.2 inch. Rear raised 1.1 in.

G. Glass Breakage. Two panes broke in glass test panel assembly No. 1 (270 ft.); the upper large one in the 90° panel, which had apparently been pulled out towards the explosion, fell in one piece and broke on striking the platform; and the lowest large pane in the 60° panel, which was fractured in place, most of the pieces falling toward the explosion. Putty was broken on most of the windows of No. 1, some was dislodged on No. 3. No glass was broken on No. 2 or No. 3, and there was no apparent effect of any sort on No. 3.

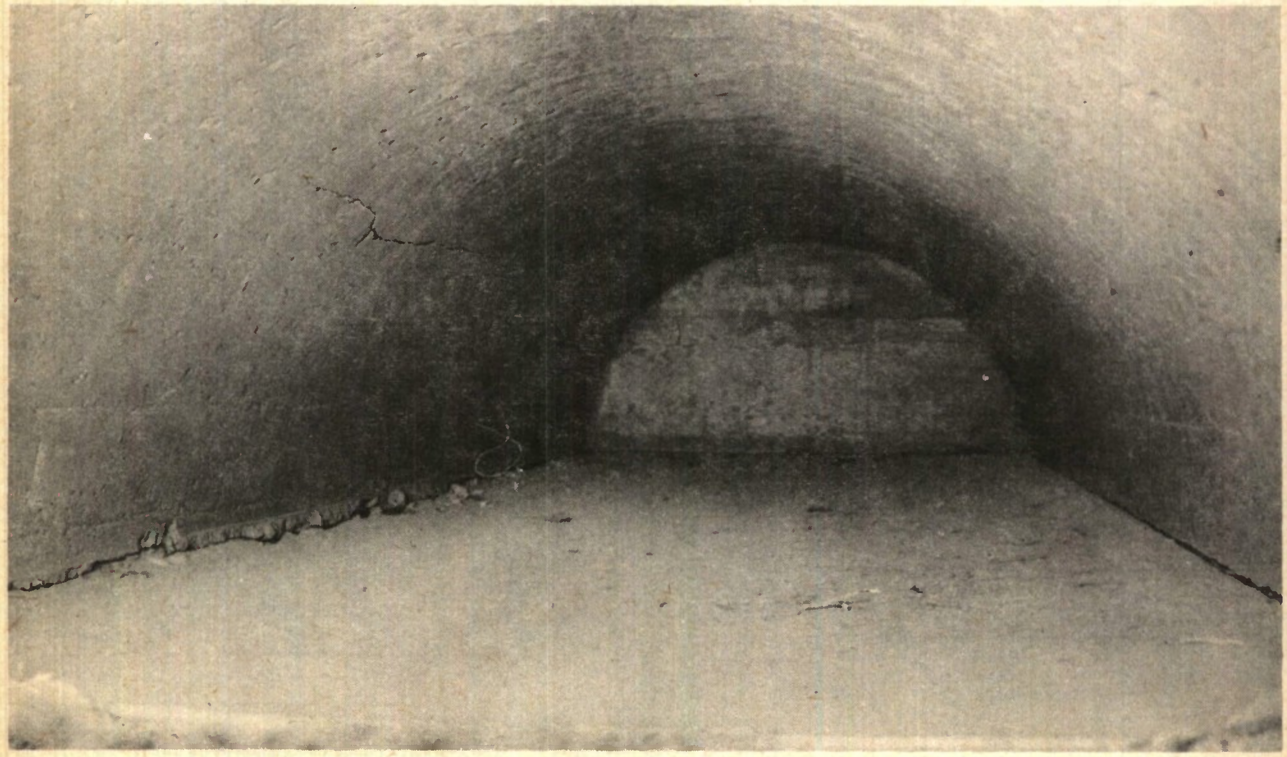
H. Air Blast. The Aberdeen paper blast meters and the aluminum foil gages registered much greater peak pressures than in the 250-pound test series, about 73 p. s. i. being obtained at 15 feet and 0.8 p. s. i. at 400 feet off the side of the primary igloo. The NOL ball crusher gages were used again in this test, but the pressure values obtained are inconsistent. The pressure data are given in table XIV and plotted on logarithmic paper in figure 46.

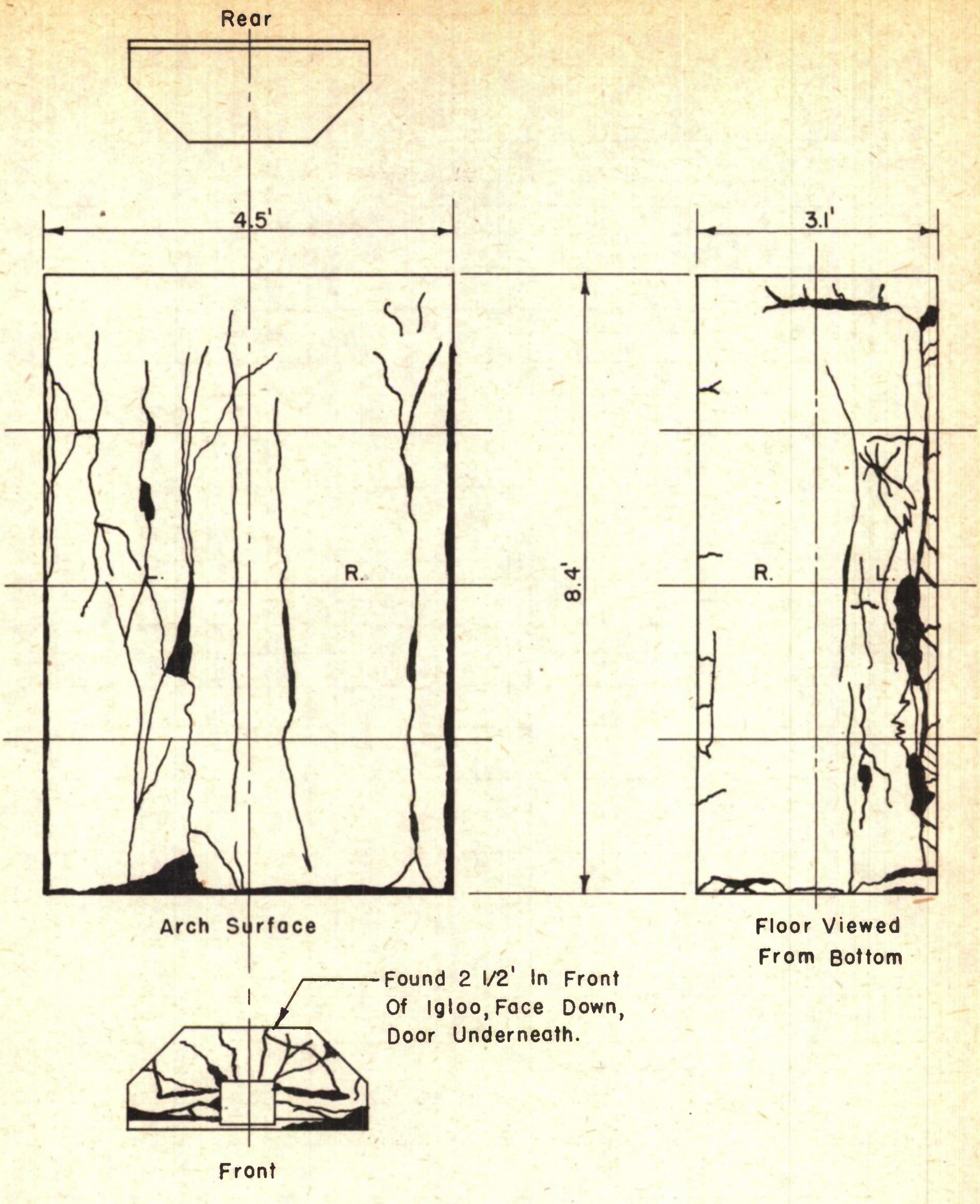
I. Fragmentation. There was more complete fragmentation of the concrete than in the 250-pound tests. No large pieces of concrete were found, even in the crater. In digging down to the bottom of the loose earth in order to obtain the true depth of the crater, some concrete fragments, apparently of the base slab, were found. These were of the order of 2 to 4 inches in largest dimension. The side of fragments decreased rapidly with distance, a few 2-inch pieces being found within 20 feet of the crater's edge and no concrete at all being found beyond approximately 100 feet. Pieces of bangalore torpedo casing were widely scattered, the farthest being found at approximately 350 feet.

6. Test No. 5, Fired at 1530, 5 August 1946.

A. Field Arrangement. Primary and target igloos, according to figure 2 and illustrated in the photograph, figure 47. Earth cover on the primary igloo was Shape No. 2 of figure 9; on the target igloo it was standard. Charge weight, 500 pounds.

Figure 44. Interior of target igloo after shot, Test 4.





Shape I Earth Cover On Primary Igloo
Charge Weight 500#

FIG. 45
DIAGRAM OF CRACKING
TARGET IGLOO
Model Test No.4

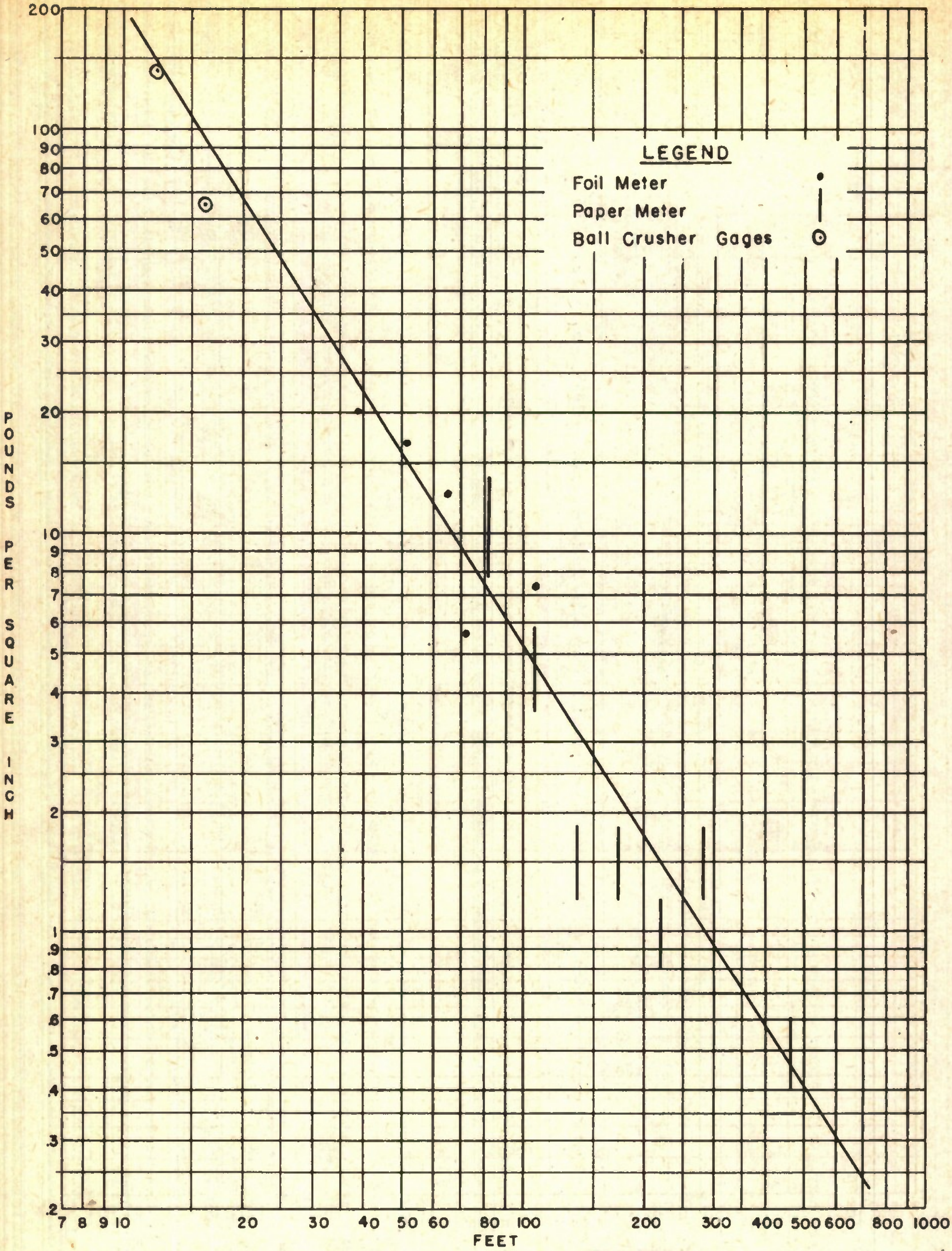


FIG.46A

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 4 Line No. 1 (Off Front)

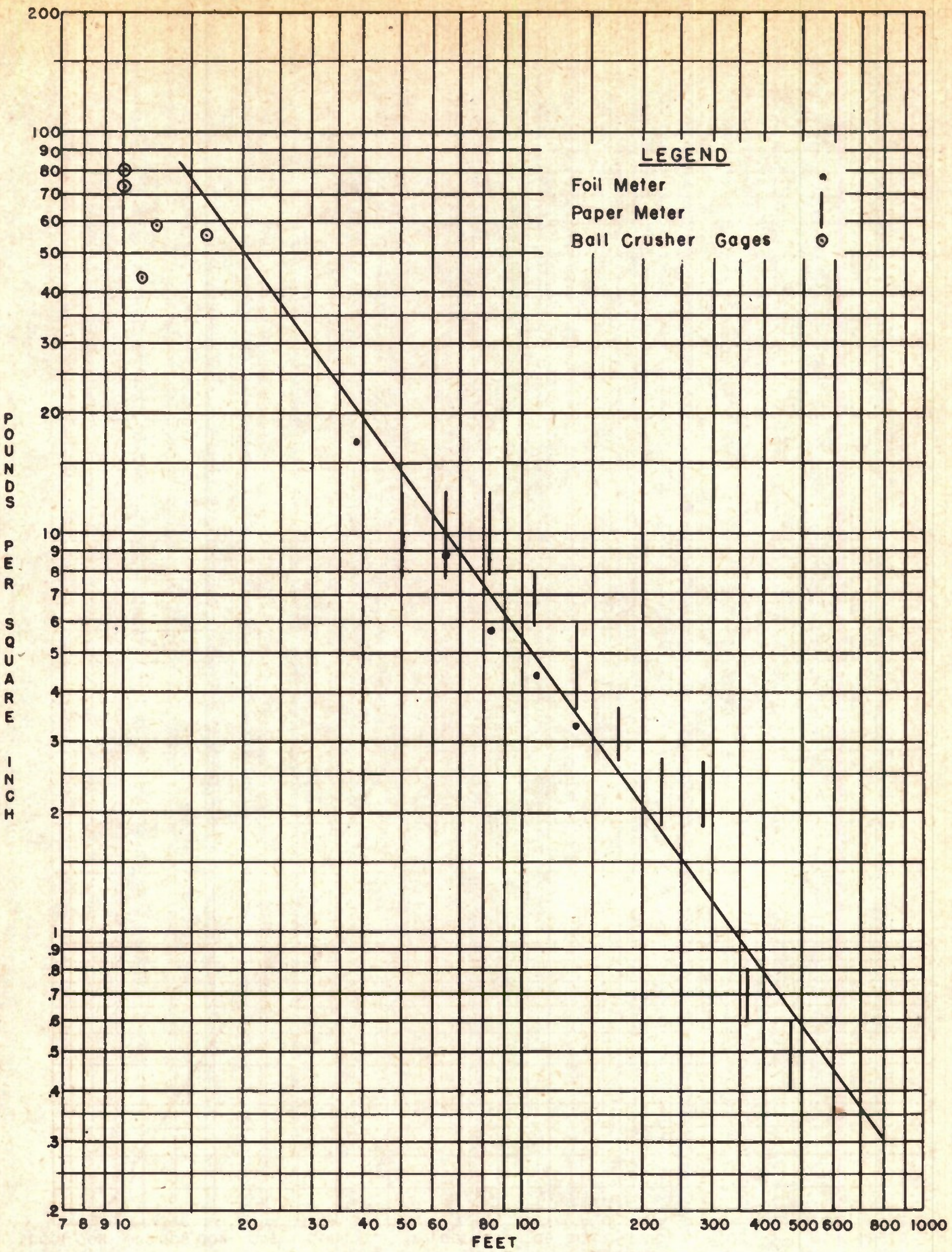


FIG.46B

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 4 Lines No.2&4(Off Sides)

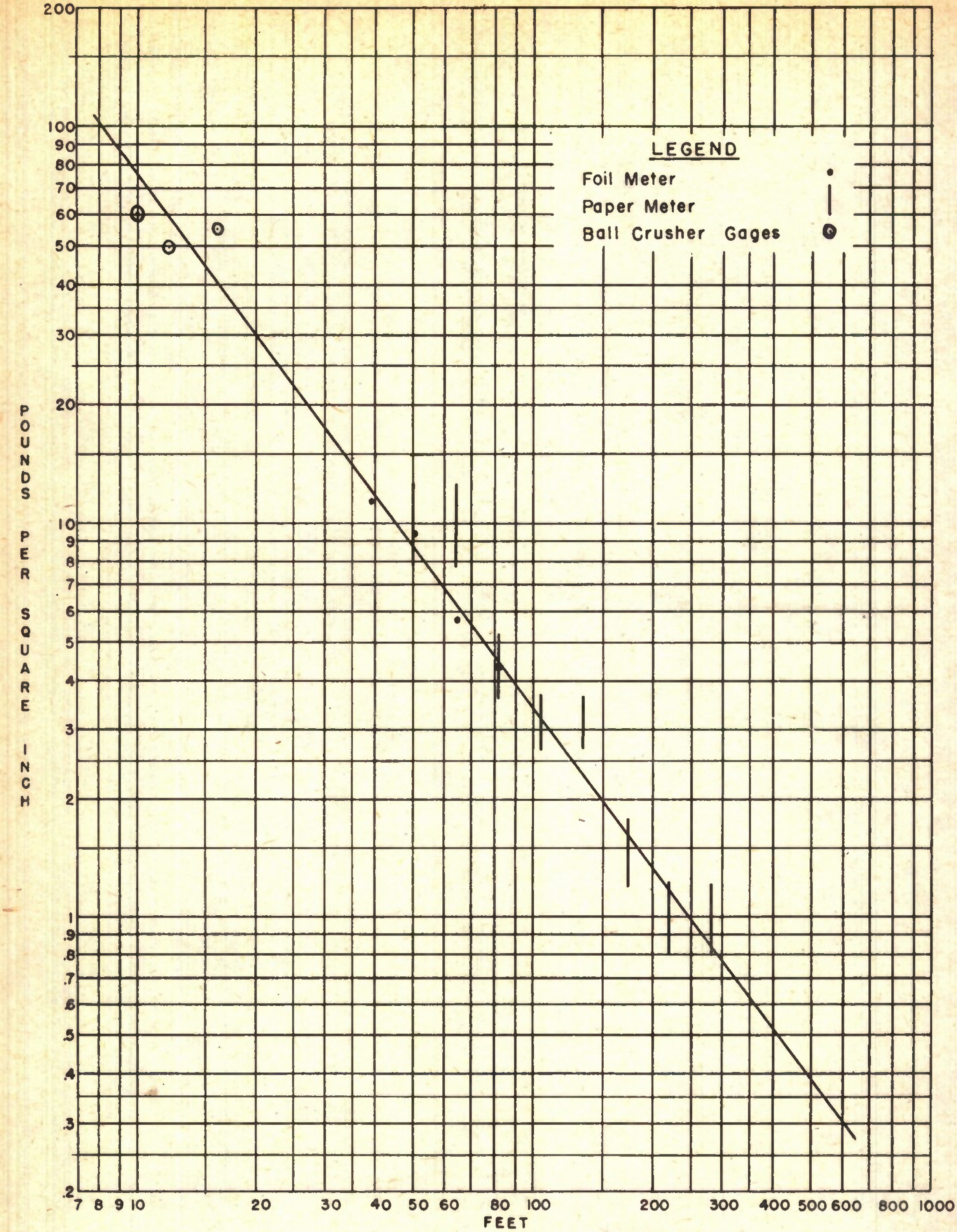


FIG.46C

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No.4 Line No. 3 (Off Rear)

Figure 47. Field arrangement, Test 5, primary igloo at left.

B. Description of Explosion. A high order detonation with a bright flash followed by a large brown dust and smoke cloud which was swept rapidly away by the southwest wind, which was blowing at a rate of from 15 to 20 m. p. h. The sky was clear. The charge was detonated by means of 14 caps energized from a 30-cap exploder, according to plan.

C. Crater. The crater was nearly uniformly round, with a diameter of 16 feet. It was cone-shaped, the deepest point being at the center where the apparent depth was 3.3 feet and the true depth 4.8 feet. The sides sloped almost uniformly from lip to bottom, figures 48 and 49.

D. Earth Displacement. Values of permanent horizontal and vertical ground movement are presented in table XV and plotted on the graphs, figures 69 and 70.

E. Damage to Target Igloo. The earth cover was severely roughened and deformed. The front end wall was badly cracked, torn loose from the top of the igloo, and remained hanging outward at an inclination of about 60° to the vertical. Its lower edge was still joined to the arch and base slab. For illustrations, see figures 50 and 51. The steel-plate door was found, badly bent, lying 8 inches inside the igloo. On the near side of the arch barrel throughout the middle third of its length and extending from 4 to 12 inches above the base slab, there appeared a network of cracks, finer and less extensive than those of Shot 4. A transverse crack extended from base to crown and partly down the far side, at 5 feet from the front end. A longitudinal crack appeared along the crown almost all the way from front to rear. On the near side, the junction of the arch barrel with the base was broken from the front to within a foot of the rear wall, and the bottom edge of the barrel was raised 1 inch above the floor at the front end. On the far side, the arch barrel-floor slab junction was broken one-third of the way back from the front, and the front end of the arch was lifted ½ inch above the floor. There were no longitudinal cracks in the far side of the barrel, and no cracks in the rear end wall. The floor slab sustained considerable longitudinal cracking. The cracking is illustrated by the sketches, figure 52. As in the previous test, the steel channels comprising the dummy

TABLE XIV

PEAK BLAST PRESSURE, P. S. I. GAGE, TEST 4

(a) Aberdeen Paper Blast Meters and Plywood Box Foil Meters

Distance from charge (feet)	Paper			Foil		
	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
38	....	....	....	20.0	16.8	11.5
50	>12.6	7.7–12.6	7.7–12.6	16.5	14.7	9.4
64	>12.6	7.7–12.6	7.7–12.6	12.5	9.4	5.6
82	7.7–12.6	7.7–12.6	3.6– 5.2	5.6	5.6	4.4
106	3.6– 5.8	5.8– 7.7	2.7– 3.6	7.25	4.4	<3.3
135	1.2– 1.8	3.6– 5.8	2.7– 3.6	3.3	3.3	<3.3
173	1.2– 1.8	2.7– 3.6	1.2– 1.8	<3.3	<3.3	....
222	.8– 1.2	1.8– 2.7	.8– 1.2	....	....	....
285	1.2– 1.8	1.8– 2.7	.8– 1.2	....	....	....
365	.6– .8	.6– .8	< .4	....	....	....
469	.4– .6	.4– .6	< .4	....	....	....
600	< .4	< .4	< .4	....	....	....

(b) Ball Crusher Gages

Meter line	Distances from charge-feet	Deformation, in. × 10^6	Calibration, in. × 10^6 lb/in.^{2}	Pressure lb/in.^{2}
1	10	10,200	29.8	342
1	12	4,300	30.2	142
1	16	2,000	30.7	65.0
2	10	2,200	29.8	73.9
2	12	1,300	30.2	43.0
2	16	1,700	30.7	55.3
3	10	1,800	29.8	60.4
3	12	1,500	30.2	49.7
3	16	1,700	30.7	55.4
4	10	2,400	29.8	80.5
4	12	1,800	30.2	59.6
4	16	400	30.7	13.0

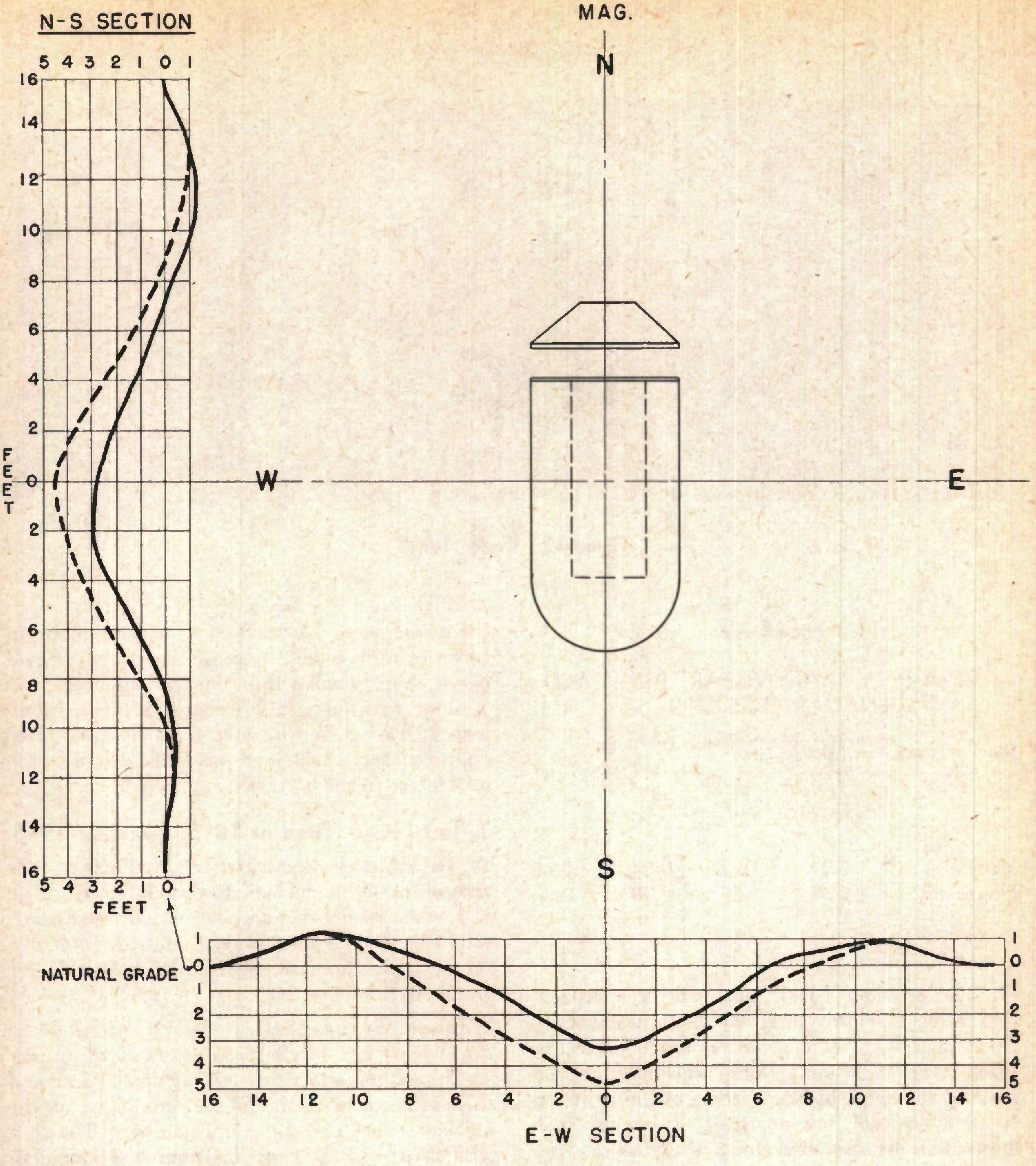
charge were severely shaken up, those on the top layer being overturned and some having fallen into the aisle.

F. Displacement of Target Igloo. (1) Transient: The floor gage registered a heave of $^{15}/_{32}$ inch; the arch-floor gage a decrease in arch-floor distance on the centerline of $^{5}/_{32}$ inch. The latter gage was broken, so the deflection may have been greater.

(2) Permanent: Transverse: Front end moved 1 inch toward; rear end 1¾ inches toward.

Longitudinal: No movement.

Elevation: Front end (floor ledge) moved down 0.4 inch. Rear end (headwall) raised 0.7 inch.



LEGEND

—— Apparent Crater

--- Estimated True Crater

FIG. 48

CRATER PROFILES

Model Test No. 5

Figure 49. Crater, Test 5.

TABLE XV

AVERAGE PERMANENT EARTH DISPLACEMENT IN INCHES, SHOT 5

Distance from center of charge, feet	13	18	23	28
Vertical	+2.24	+1.27	+0.84	+0.48
Horizontal	+2.30	−1.28	−.48	0

G. Glass Breakage. Only one pane was broken, that being the lower large 90° pane in assembly No. 1 (270 feet). The glass was broken outward, toward the explosion. Putty was disturbed on most of the lights of No. 1, some of the lights on No. 2 (360 feet), but no effect of any sort was discernible on assembly No. 3 (541 feet).

H. Air Blast. The paper meters and aluminum foil gages gave consistent readings and the pressures are about the same as those obtained in Shot 4. The ball crusher gages afforded some readings but they varied widely. The pressure values from the three types of gages are tabulated in table XVI and plotted on figure 53.

I. Fragmentation. As in Shot 4, no large pieces of concrete were found, even in the crater. Small pieces were found within 100 feet, their size decreasing with distance. Fragments of bangalore torpedo casing were scattered widely; one piece approximately 1 inch long was found at a distance of 500 feet to the northeast.

7. Test No. 6, Fired at 1015, 8 August 1946.

A. Field Arrangement. Two hundred fifty pounds amatol in 28 bangalore torpedoes stored in a 1/10th scale model of an open storage revetment; target igloo, 21.4 feet away, center-to-center distance, with standard earth cover. See figures 7 and 10.

B. Description of Explosion. A high order detonation, showing a bright flash followed by a grey smoke column which rose to about 300 feet and then mushroomed. It diffused gradually, as the air was still. The sky was cloudless. The shot was fired with 7 caps distributed at random throughout the stack of bangalores, according to plan.

C. Crater. Nearly symmetrical, with almost uniformly sloping sides, a large lip and a slight mound or rise in the bottom. The diameter was 11.2 feet, apparent depth, 1.8 feet and true depth 3.2 feet. See figures 54 and 55.

TABLE XVI

PEAK BLAST PRESSURES, P. S. I. GAGE, TEST 5

(a) Aberdeen Paper Blast Meters and Plywood Box Foil Meters

Distance from charge (feet)	Paper			Foil		
	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3
38	....	....	....	22.0	12.5	9.4
50	>12.6	7.7–12.6	7.7–12.6	16.5	9.4	7.25
64	7.7–12.6	7.7–12.6	5.8– 7.7	11.5	7.25	4.4
82	5.8– 7.7	5.8– 7.7	3.6– 5.8	7.25	4.4	3.3
106	3.6– 5.8	3.6– 5.8	1.2– 1.8	4.4	3.3	<3.3
135	1.8– 2.7	2.7– 3.6	1.2– 1.8	4.4	<3.3	<3.3
173	1.8– 2.7	1.8– 2.7	.8– 1.2	<3.3	<3.3	....
222	.6– .8	1.2– 1.8	.8– 1.2	....	....	....
285	.6– .8	.8– 1.2	.6– .8	....	....	....
365	.6– .8	.8– 1.2	<.4	....	....	....
469	<.4	<.4	<.4	....	....	....
600	<.4	<.4	<.4	....	....	....

(b) Ball Crusher Gages

Meter line	Distances from charge-feet	Deformation in. X 10^6	Calibration, in. X 10^6 /lb./in.^{2}	Pressure, lb./in.^{2}
1	10	10,100	29.8	339
1	12	10,400	30.2	344
1	16	6,700	30.7	218
2	10	1,300	29.8	43.6
2	12	2,700	30.2	89.4
2	16	1,200	30.7	39.1
3	10	1,500	29.8	50.3
3	12	900	30.2	29.8
3	16	900	30.7	29.3
4	10	2,000	29.8	67.1
4	12	100	30.2	....
4	16	0	30.7	....

D. Earth Displacement. Values of permanent horizontal and vertical ground movement at various distances are given in table XVII and plotted on the graphs, figures 69 and 70.

E. Damage to Target Igloo. The earth cover was roughened and considerably deformed. The front end wall sustained several severe cracks and was loosened from the base slab. The arch sustained two longitudinal cracks about half the length of the barrel, one in the upper part of the near side and one at the crown. It also suffered a transverse crack starting at the base on the near side, running over the crown and nearly down to the base on the far side, located just back of the front end wall. Two other transverse cracks appeared near the middle of the barrel, one running almost

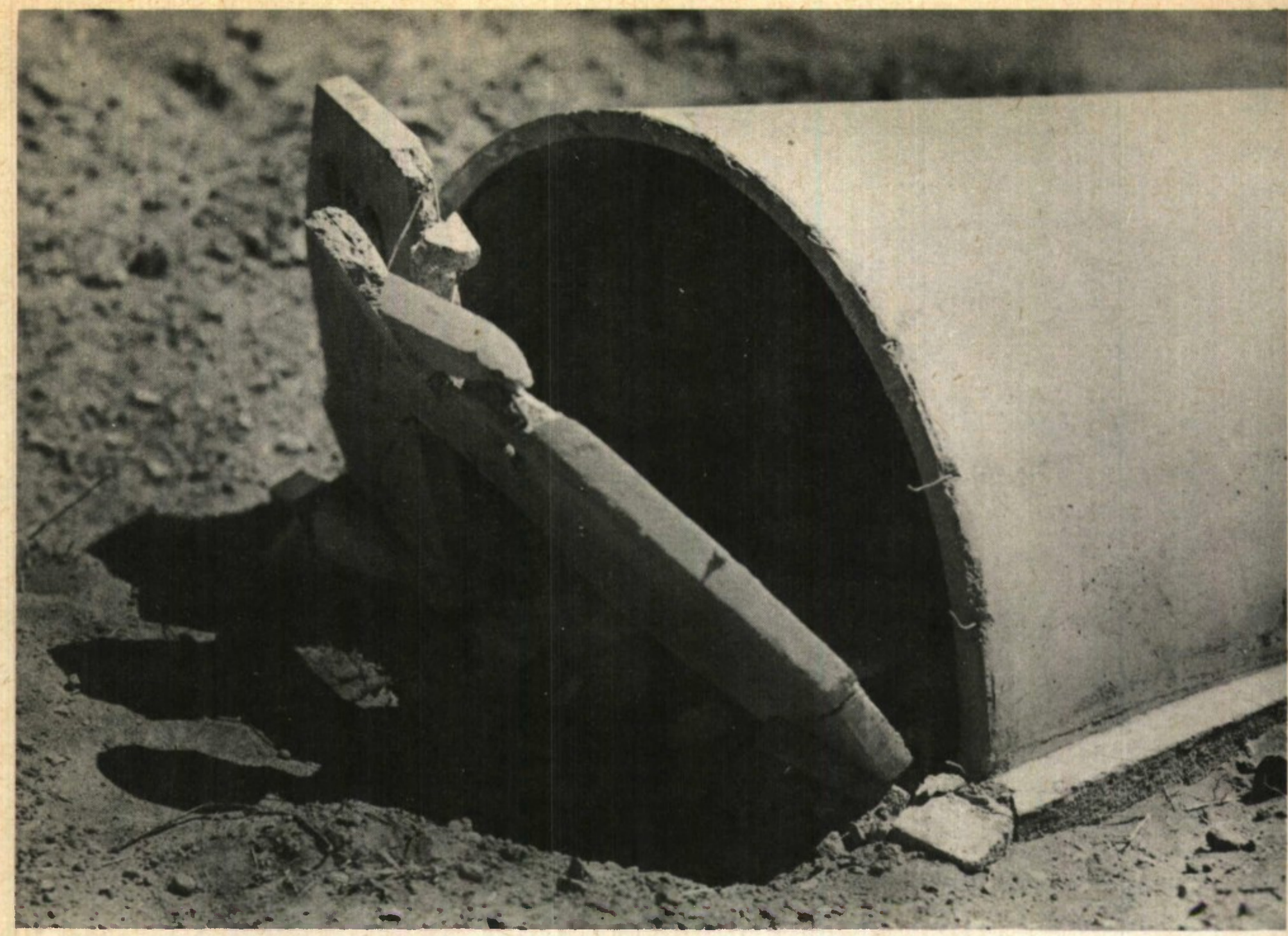
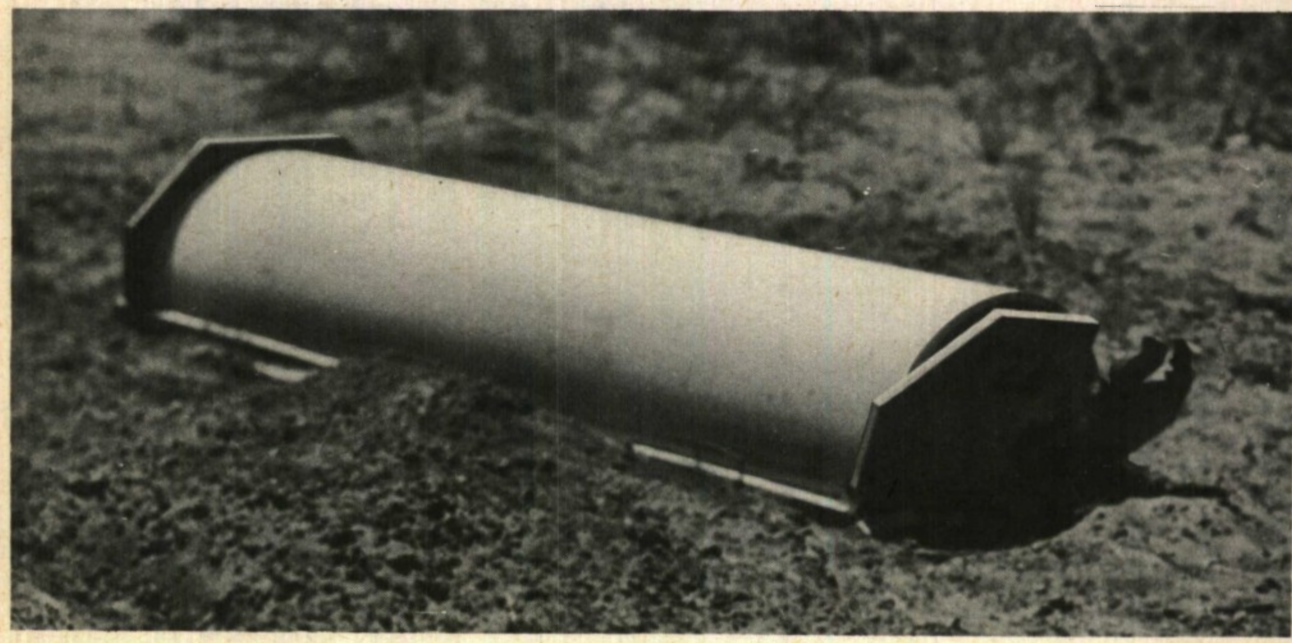
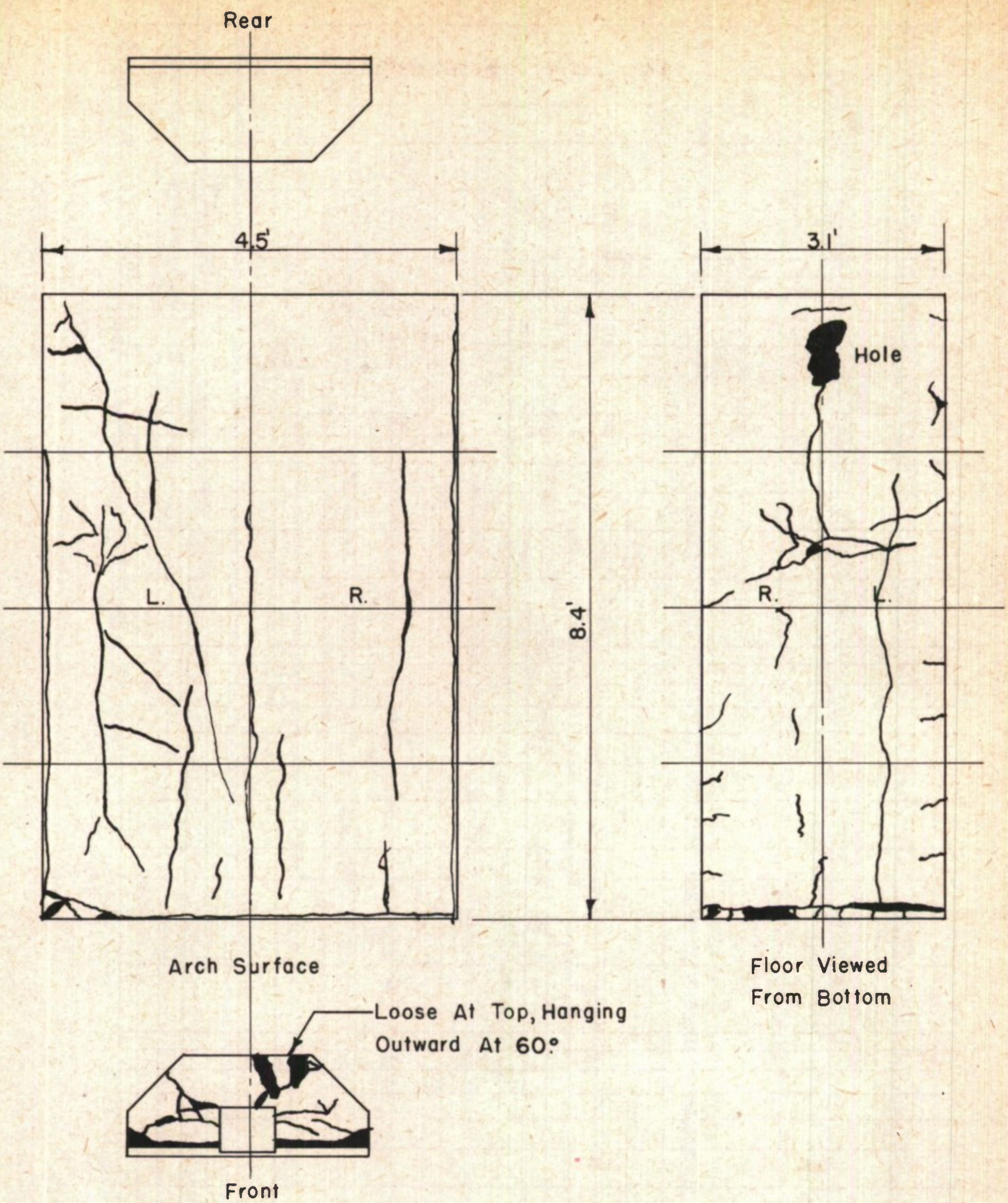


Figure 50. Front of target igloo, after shot, Test 5.

Figure 51. Target igloo, Test 5, after shot and removal of earth cover.





Shape 2 Earth Cover On Primary Igloo.
Charge Weight 500#

FIG.52
DIAGRAM OF CRACKING
TARGET IGLOO
Model Test No.5

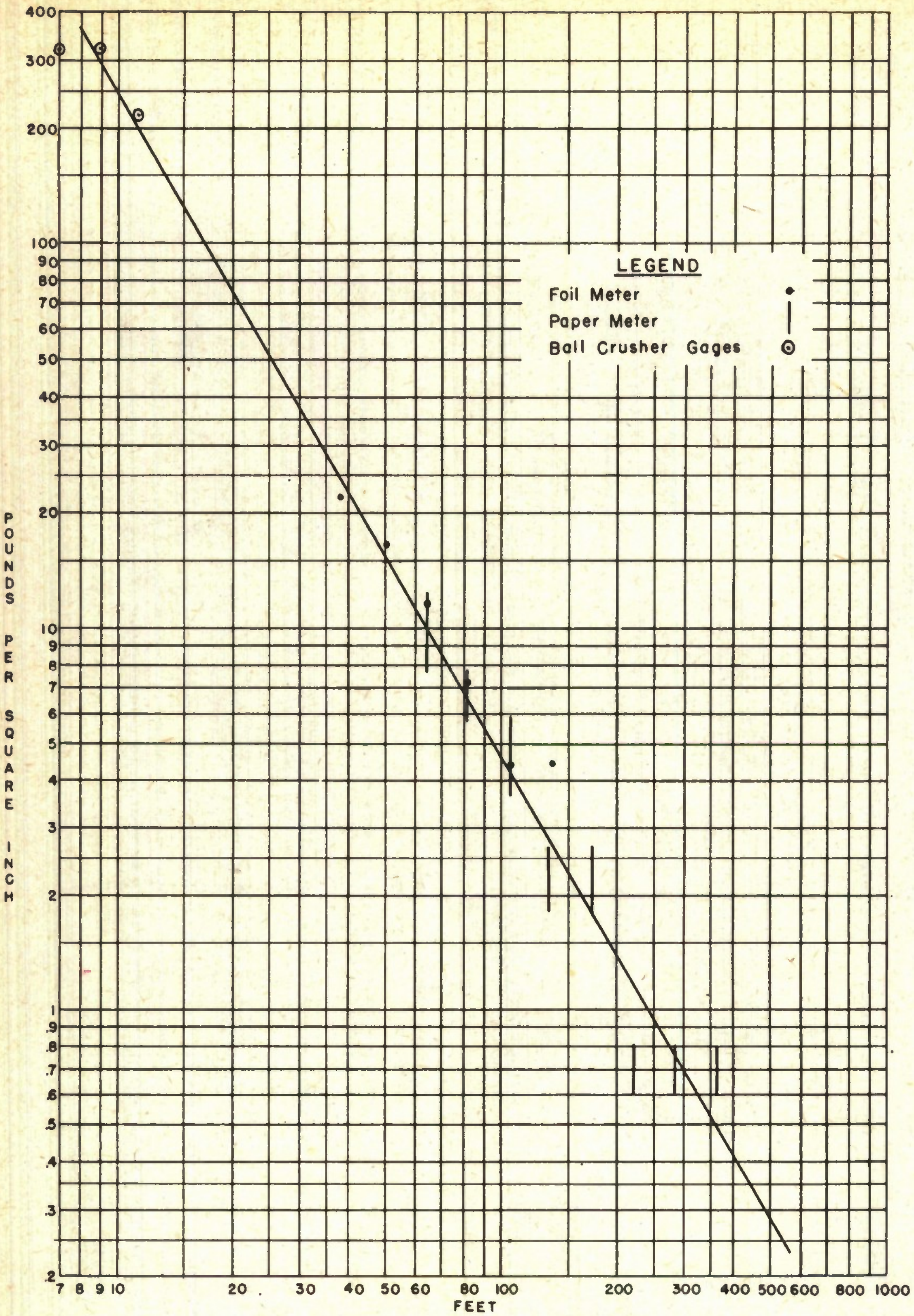


FIG.53A

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No.5 Line No.1 (Off Front)

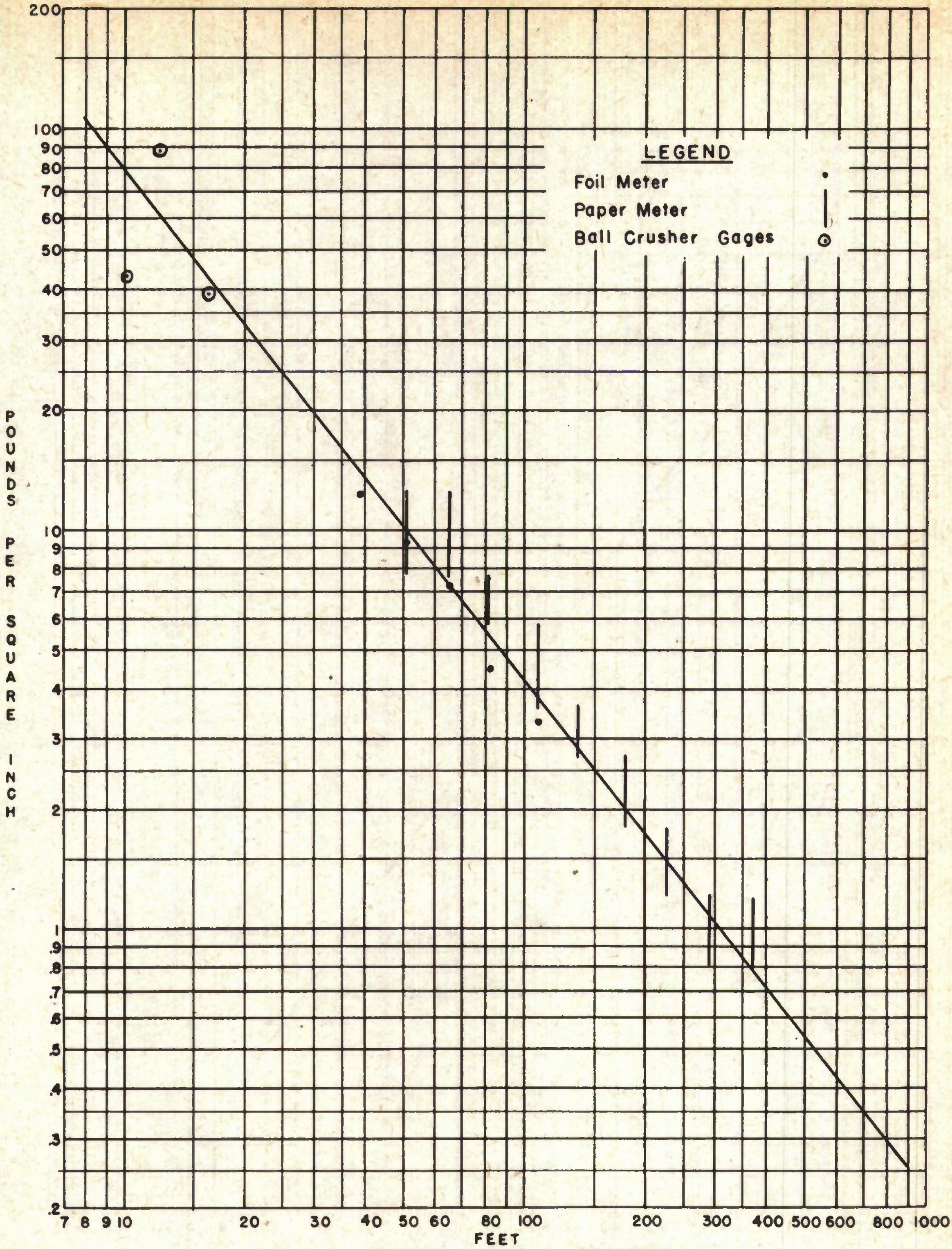


FIG.53B

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No.5 Line No.2 (Off Side)

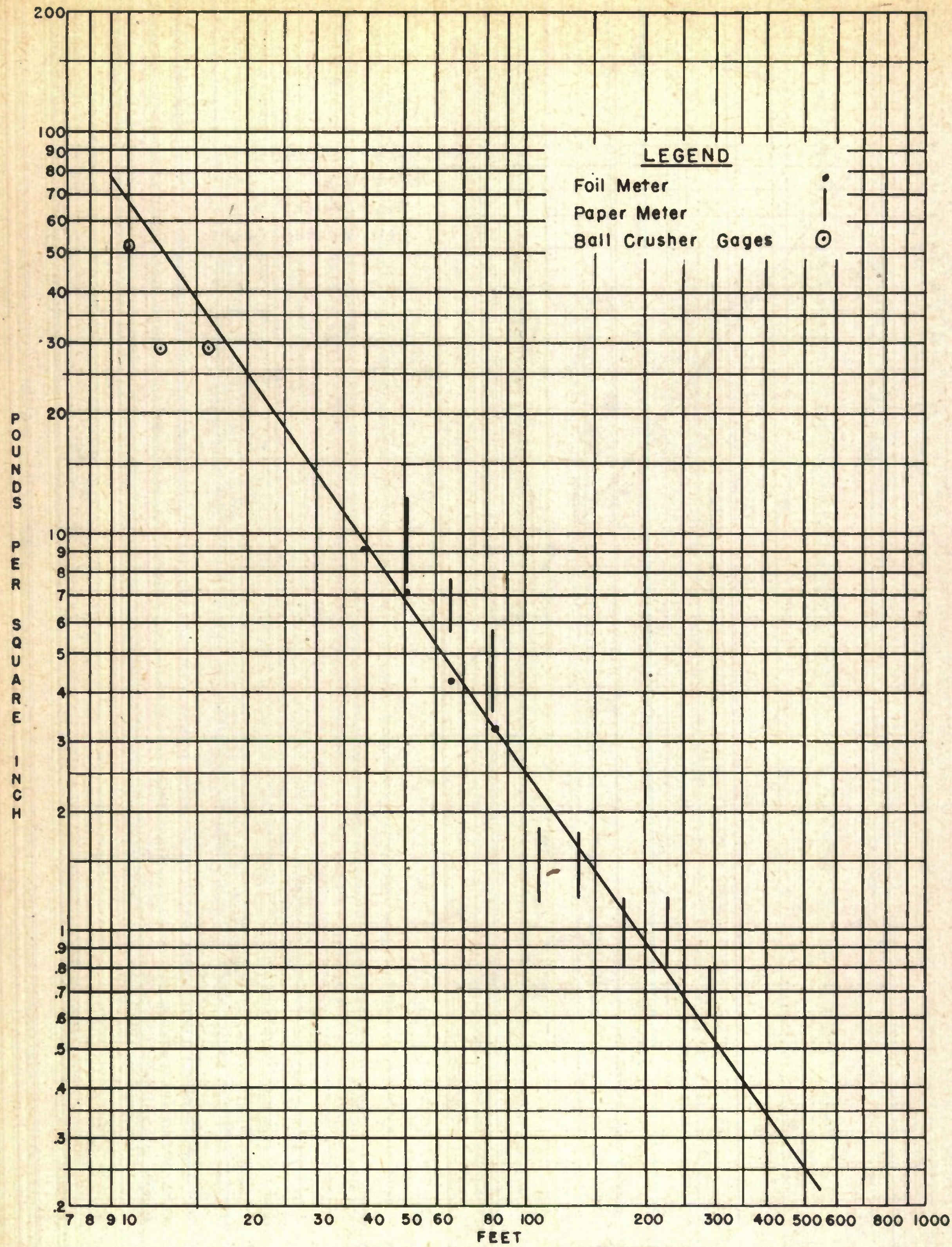


FIG.53C

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No.5 Line No.3 (Off Rear)

Figure 54. Crater, Test 6.

TABLE XVII

AVERAGE PERMANENT EARTH DISPLACEMENT IN INCHES, SHOT 6

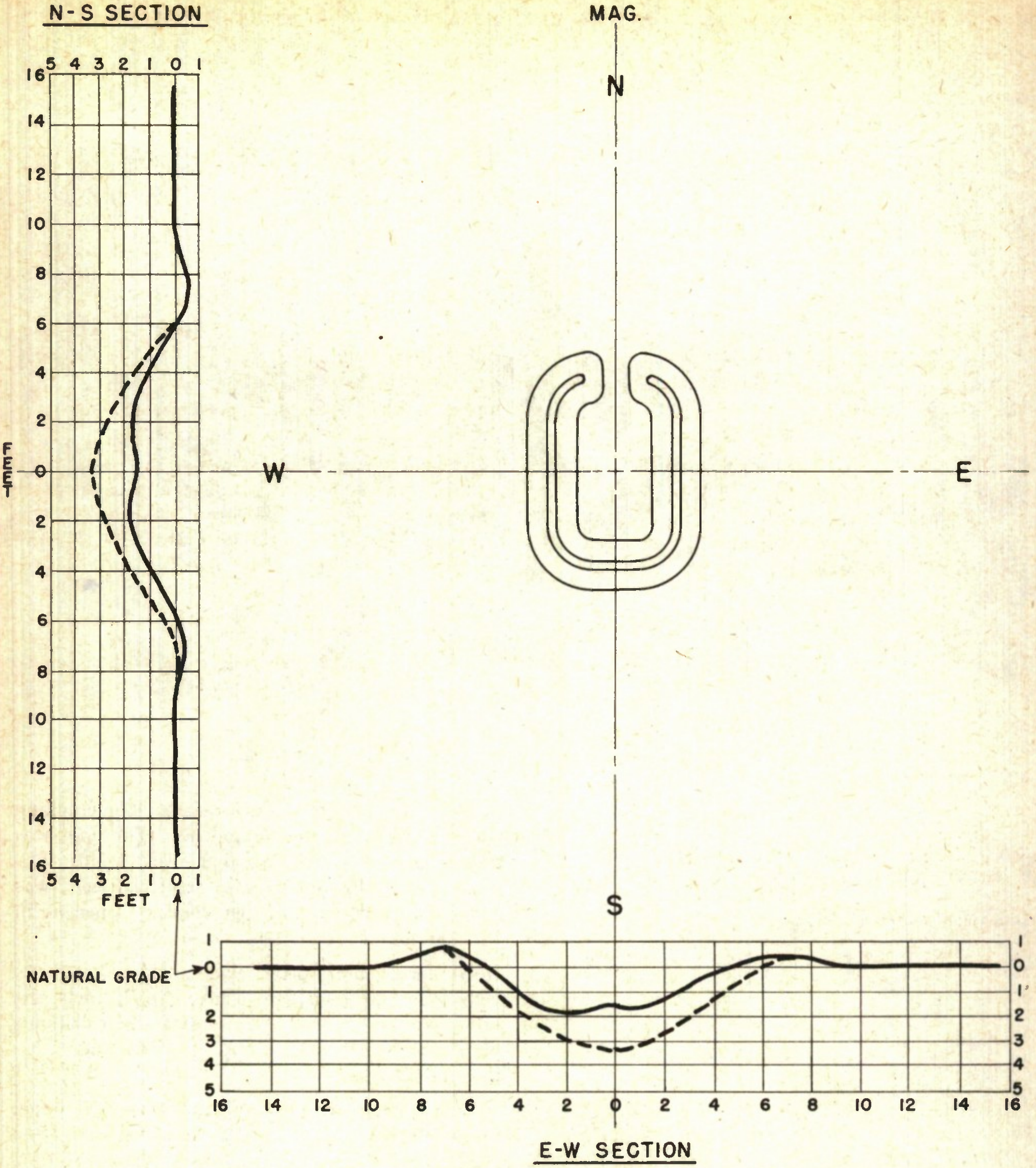
Distance from center of charge, feet

	8	13	18	23
Vertical.....	+1.25	+0.40	+0.15	+0.15
Horizontal...	+2.18	−.10	0	0

all the way over the arch and the other running somewhat beyond halfway over the arch. One of these had existed prior to the shot, and was made worse. A longitudinal crack occurred in the floor slab, about 4 inches in from the near edge, running about three-quarters of the length of the igloo. A crack appeared at the junction of the rear end wall with the base slab, running halfway across from the near edge. The cracking is illustrated in figures 56 and 57. The door was undamaged but its latchbar was bent. The dummy charge, consisting of steel channels, was shaken up but was not disturbed as much as in the 500-pound tests.

F. Displacement of Target Igloo. (1) Transient: The floor gage registered a heave of $^{13}/_{32}$ inch; the arch-floor gage a decrease in arch-to-floor distance on the centerline of $^{1}/_{16}$ inch. (2) Permanent: No movement detected.

G. Glass Breakage. In this test, glass test panel assemblies were placed at the following distances: No. "0", 144 feet; No. 1, 215 feet; No. 2, 287 feet. In assembly No. "0" all large panes, and all except one middle-sized pane in the 30° panel were broken. None of the small panes was broken, but the putty was loosened. In assembly No. 1, all three lower large panes, the upper large pane in the 90° panel, and one middle-sized pane in the 90° panel were broken. No small panes were broken. The putty was loosened on several



LEGEND

—— Apparent Crater

- - - Estimated True Crater

FIG. 55

CRATER PROFILES

Model Test No. 6

panes. In assembly No. 2, only one pane broke, that being the lower large 90° pane. Some putty was loosened on other panes. Almost all the broken glass fell out toward the explosion, in all three panel assemblies.

H. Air Blast. The peak air blast pressures measured by paper blast meters, foil blast meters, and ball crusher gages were higher than those obtained in the series in which the charge was detonated within an earth-covered igloo. The ball crusher gage readings were more consistent and credible than in the previous shots. In addition, a new ball crusher gage with a larger piston was used. This gage is described in part III, paragraph 9, hereof, and is called the Arco ball crusher gage. The deformation of the copper ball obtained with this gage was much greater than with the NOL gage, and hence could be read with a much smaller percentage of error. The pressure value obtained with this gage as well as those obtained with the other meters and gages are presented in table XVIII and plotted on logarithmic paper in figure 58.

I. Fragmentation. A number of pieces of bangalore torpedo casing were found scattered within a 400-foot radius as in the previous shots. There seemed to be less fragments than in the former tests, however.

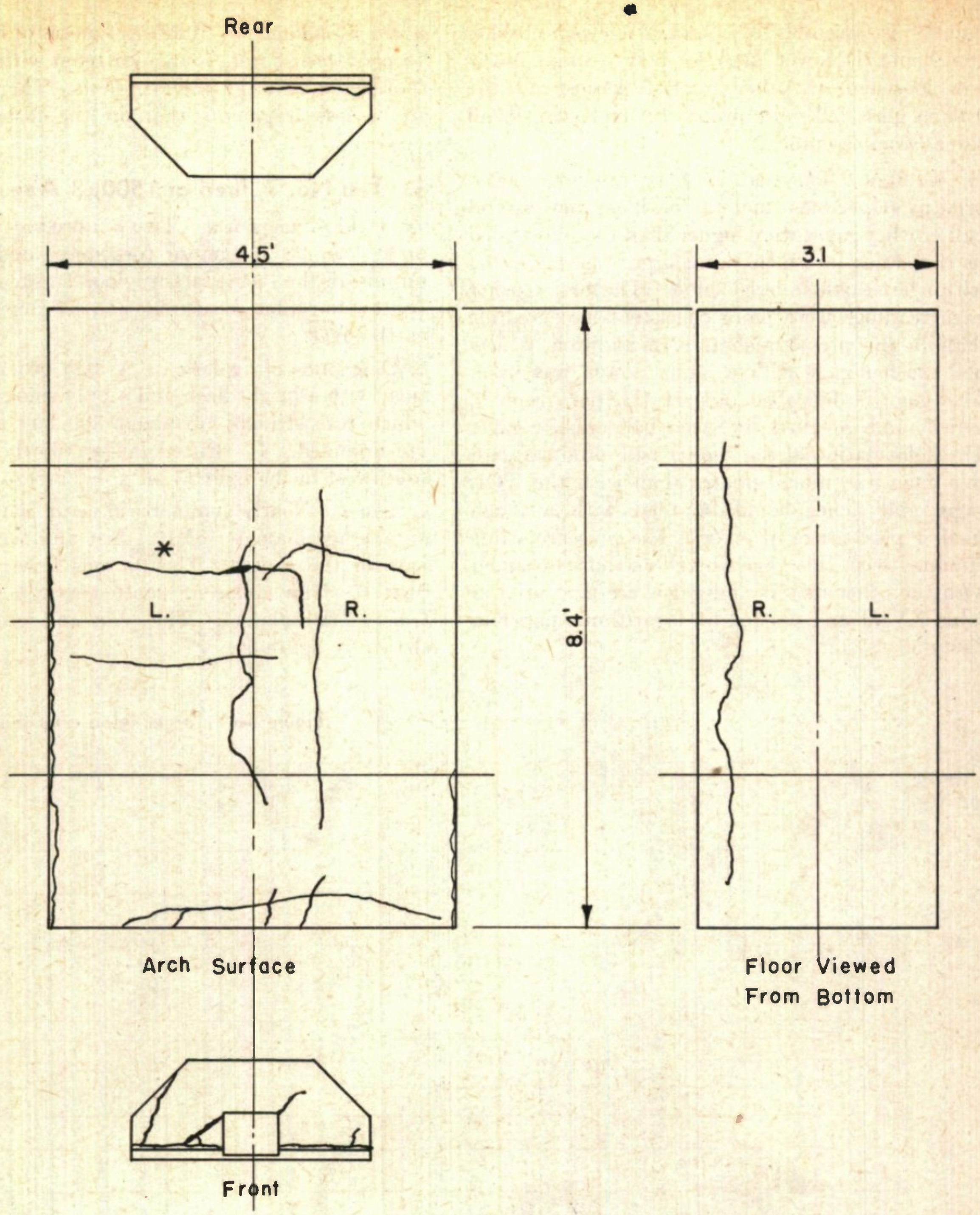
8. Test No. 7, fired at 1500, 8 August 1946.

A. Field Arrangement. Two hundred fifty pounds amatol in 28 bangalore torpedoes, laid on the ground in the open; target igloo, 21.4 feet distant (center-to-center measurement), having standard earth cover.

B. Description of Explosion. A high order detonation, with a bright flash and a grey smoke column which rose straight up about 300 feet and then mushroomed. It drifted away slowly to the southwest in the light (5 m. p. h.) breeze.

C. Crater. Nearly symmetrical as in Shot 6, with an average diameter of 10.1 feet and the deepest part in the center. The lip was lower than in Shot 6. The apparent depth was 2.5 feet, the true depth 3.9 feet. The plan and profiles are shown by figure 60.

Figure 56. Target igloo after shot, Test 6.



* Existed Before Test & Made Worse
Charge Weight 250# In Revetment

FIG.57
DIAGRAM OF CRACKING
TARGET IGLOO
Model Test No.6

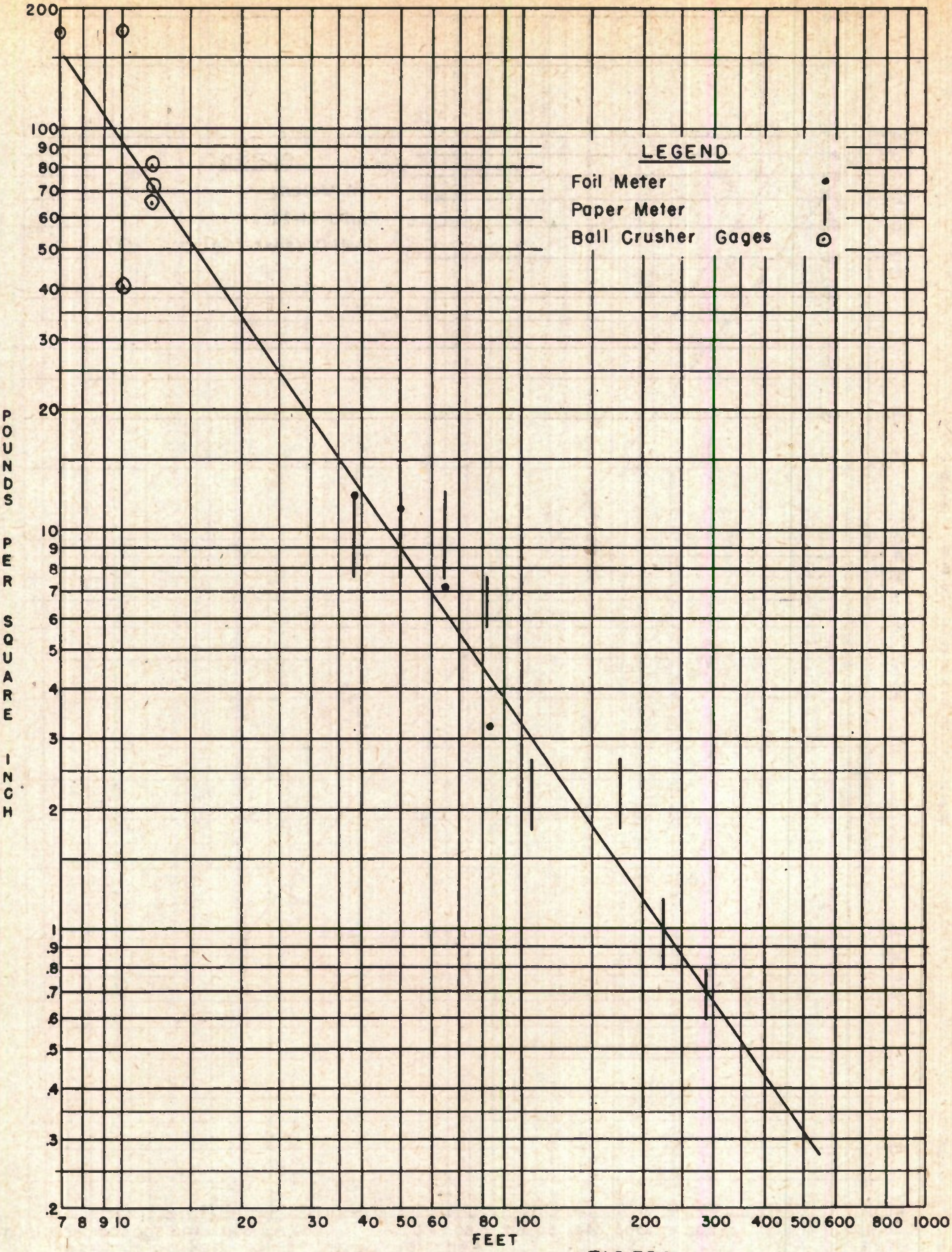


FIG.58A

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 6 Lines No.2&5(Off Sides)

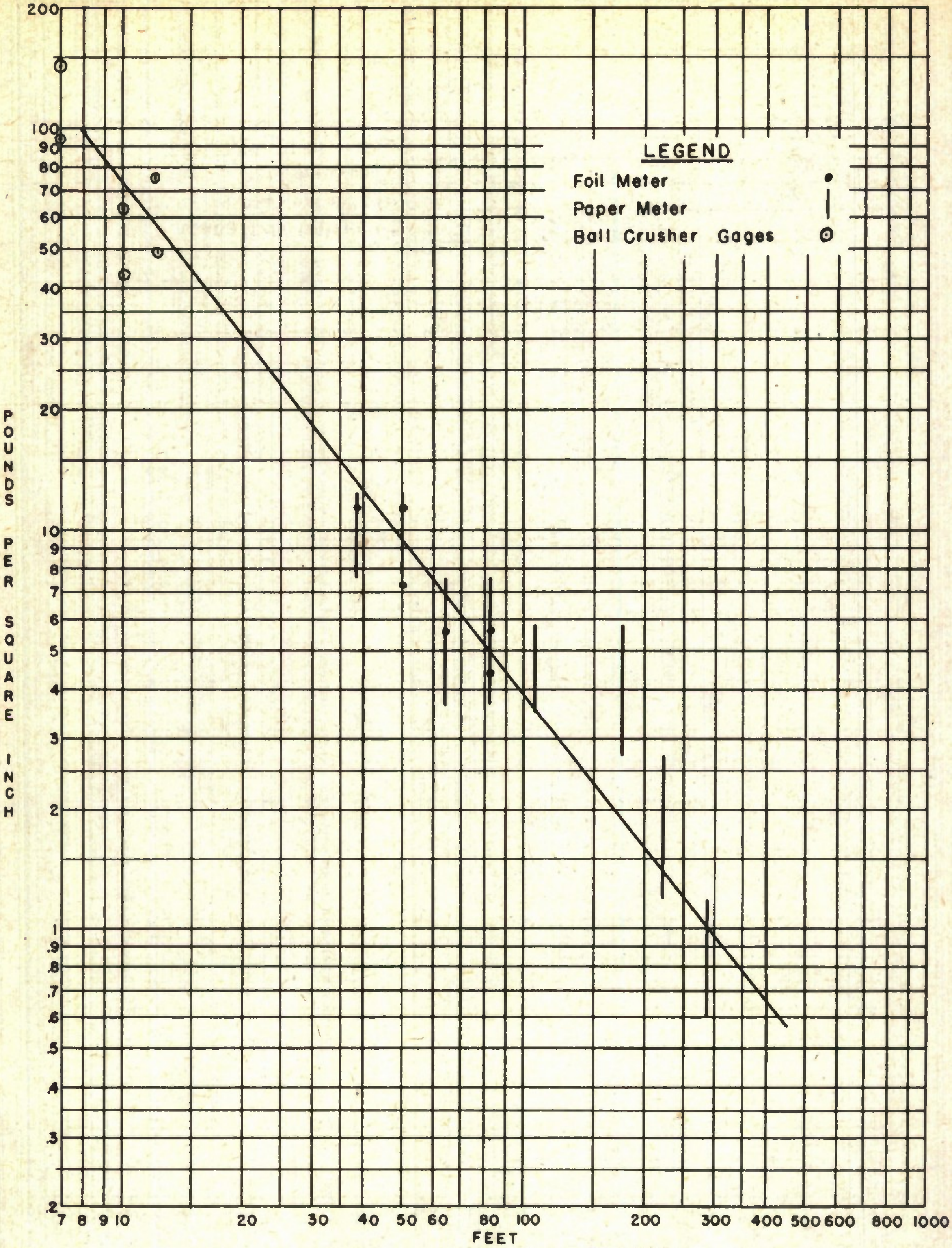


FIG. 58B

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 6 Line No. 3 (Off Ends)

TABLE XVIII

PEAK BLAST PRESSURES, P. S. I. GAGE, TEST 6

(a) Aberdeen Paper Blast Meters and Plywood Box Foil Meters

Distance from charge (feet)	Paper			Foil		
	Line 1	Line 3	Line 5	Line 1	Line 3	Line 5
38	7.7–12.6	7.7–12.6	7.7–12.6	11.5	12.5	12.5
50	7.7–12.6	7.7–12.6	7.7–12.6	7.25	11.5	11.5
64	3.6– 5.8	5.8– 7.7	7.7–12.6	5.6	7.25	7.25
82	3.6– 5.8	5.8– 7.7	5.8– 7.7	4.4	5.6	3.3
106	3.6– 5.8	3.6– 5.8	1.8– 2.7	......	......	......
173	2.7– 3.6	3.6– 5.8	1.8– 2.7	......	......	......
222	1.8– 2.7	1.2– 1.8	.8– 1.2	......	......	......
285	.8– 1.2	.6– .8	.6– .8	......	......	......

(b) Ball Crusher Gages

Meter line	Distance from charge (feet)	Deformation, in. X 10^6	Calibration, in. X 10^6 /lb./in.^{2}	Pressure, lb./in.^{2}
1	7	4,100	28.8	142.3
1	10	1,900	29.8	63.8
1	12	1,500	30.2	49.7
2	7	5,100	28.8	177.0
2	10	5,300	29.8	178.0
2	12	2,200	30.2	72.8
3	7	2,700	28.8	93.8
3	10	1,300	29.8	43.6
3	12	2,300	30.2	76.2
5	7	2,400	28.8	83.4
5	10	1,200	29.8	40.2
5	12	2,000	30.2	67.2
5	12	[1] 11,000	134	82.2

[1] Arco gage.

D. Earth Displacement. Data giving the permanent horizontal and vertical ground movement at various distances from the center of the crater are presented in table XIX, and plotted on the graphs, figures 69 and 70.

E. Damage to Target Igloo. The earth cover was partly blasted away and left considerably deformed. The front end wall suffered a number of severe cracks and a small piece was blown off over the door. The arch barrel sustained three long longitudinal cracks running about two-thirds of the length of the igloo, two on the near side and one just over the crown on the far side. Two transverse cracks appeared about 2½ feet from the front end, one on the near side of the arch and one on the far side, each being limited to its own side. A longitudinal crack about 18 inches long crossed the transverse crack on the far side near

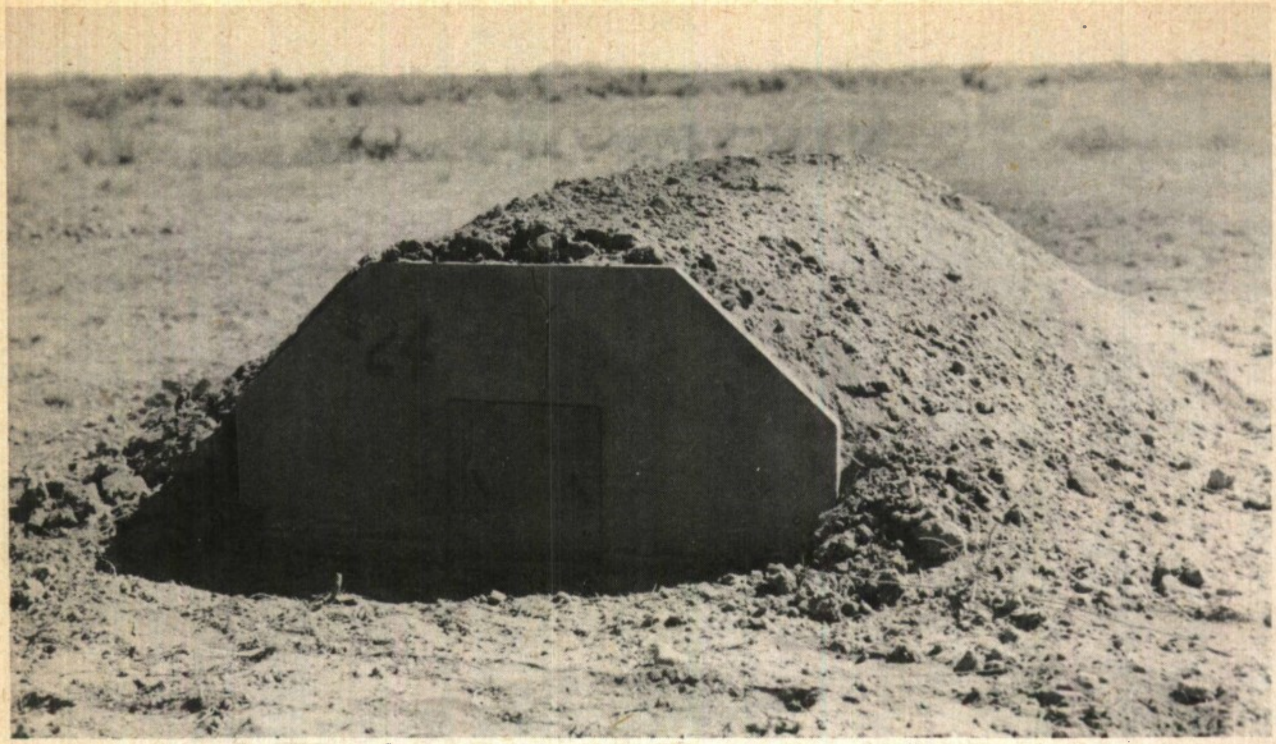


Figure 59. Target igloo after shot, Test 7.

its midpoint. A longitudinal crack appeared in the floor slab 2 to 4 inches from the near edge, running almost the length of the igloo. Another longitudinal crack appeared from 2 to 4 inches in from the far edge of the floor slab, but was about a foot shorter than the crack on the near side. The rear end wall was undamaged. The door was not damaged but the latchbar was bent. The cracking is shown by the sketches in figure 61.

F. Displacement of Target Igloo. (1) Transient: The floor gage indicated a rise of ⅜ inch; the arch-floor gage a decrease in arch-to-floor height on the longitudinal centerline of $\frac{1}{16}$ inch.
(2) Permanent: No movement.

G. Glass Breakage. The arrangement of glass test panel assemblies was the same as in Shot 6. In assembly No. "0" all large panes, all except one middle-sized pane in the 30° panel and one small pane in the 90° panel were broken. In assembly No. 1, all three lower large panes, the 60° and the 90° upper large panes, two of the 90° middle-sized panes, and all of the 90° small panes were broken. The three 30° middle-sized panes were loosened. Putty was damaged on all unbroken lights. In assembly No. 2, only the two large 90° panes were broken. In all three assemblies, almost all (an estimated 95 percent) of the broken glass fell out toward the explosion.

H. Air Blast. The pressure values obtained with the paper and foil meters, and the NOL and Arco ball crusher gages, are tabulated in table XX and plotted in figure 62. The average line is slightly higher than that of Shot 6.

I. Fragmentation. No fragments, except a few pieces of bangalore torpedo casing, were found.

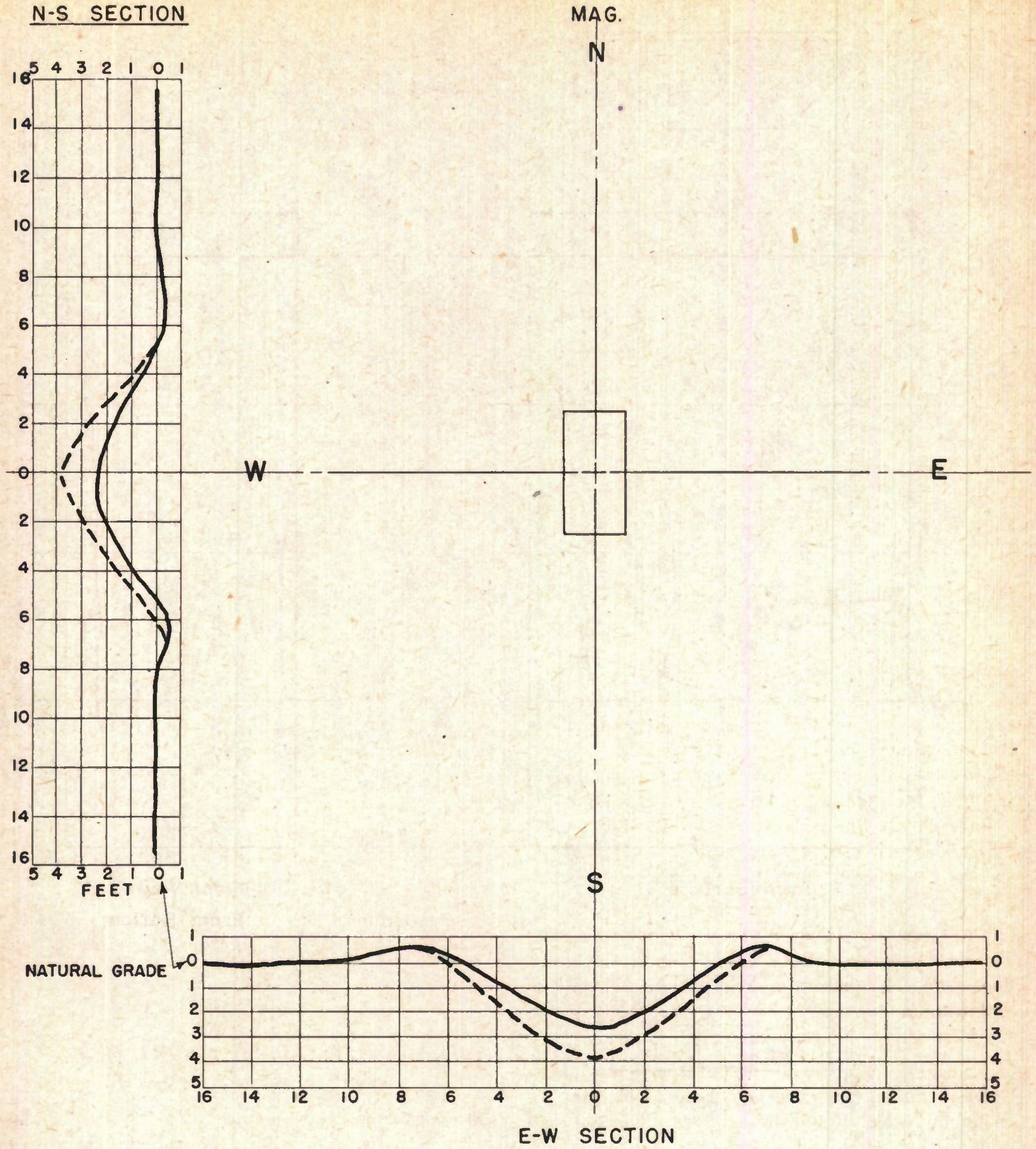
TABLE XIX

AVERAGE PERMANENT EARTH DISPLACEMENT IN INCHES, SHOT 7

Distance from center of charge, feet

	8	13	18	23
Vertical	+2.25	+0.65	+0.33	+0.20
Horizontal	+1.65	+.22	0	0

+ means up and away from explosion.



LEGEND

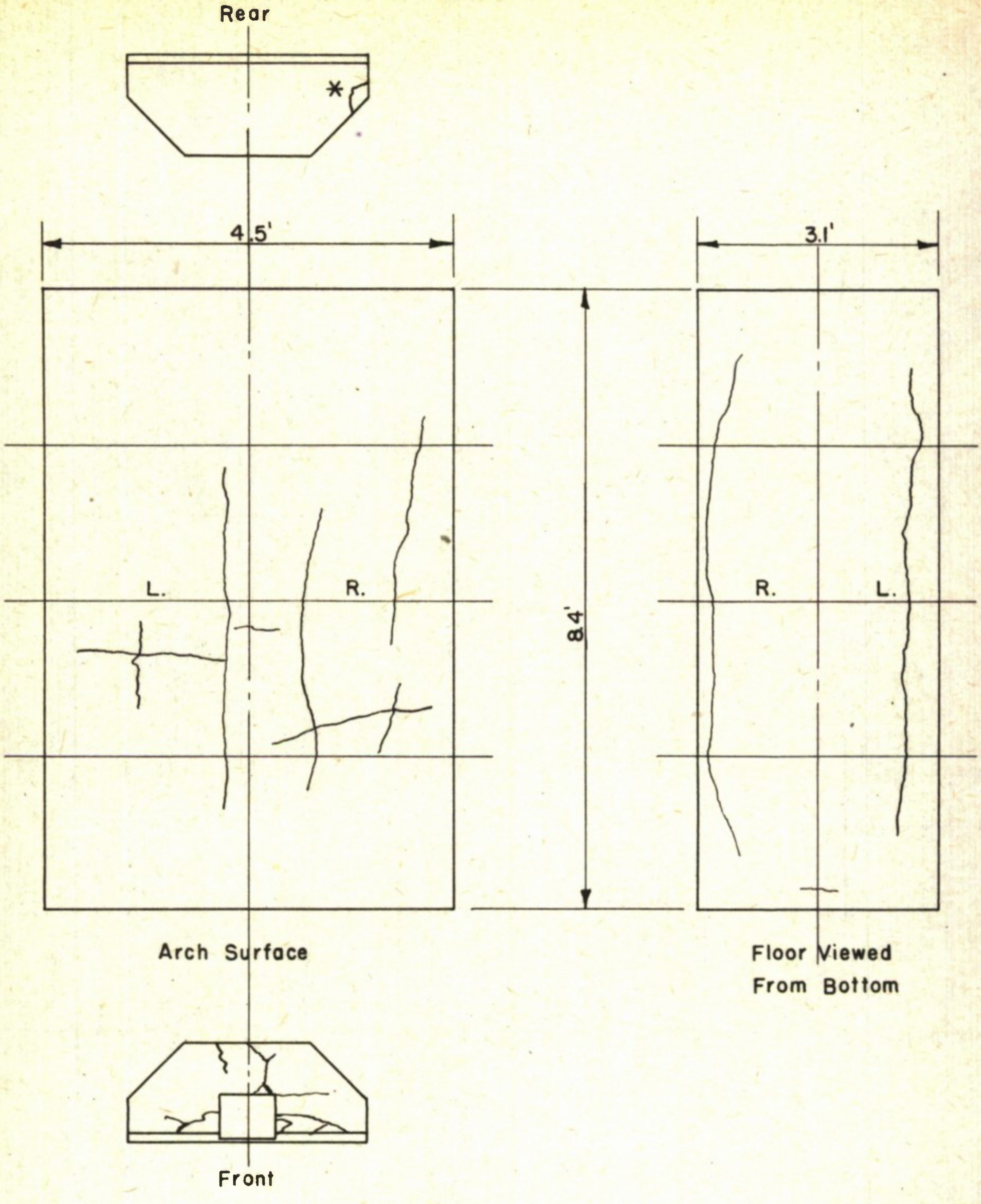
—— Apparent Crater

- - - Estimated True Crater

FIG. 60

CRATER PROFILES

Model Test No. 7



* Crack Existed Prior To Test.
Charge Weight 250# In Open Pile

FIG. 61
DIAGRAM OF CRACKING
TARGET IGLOO
Model Test No. 7

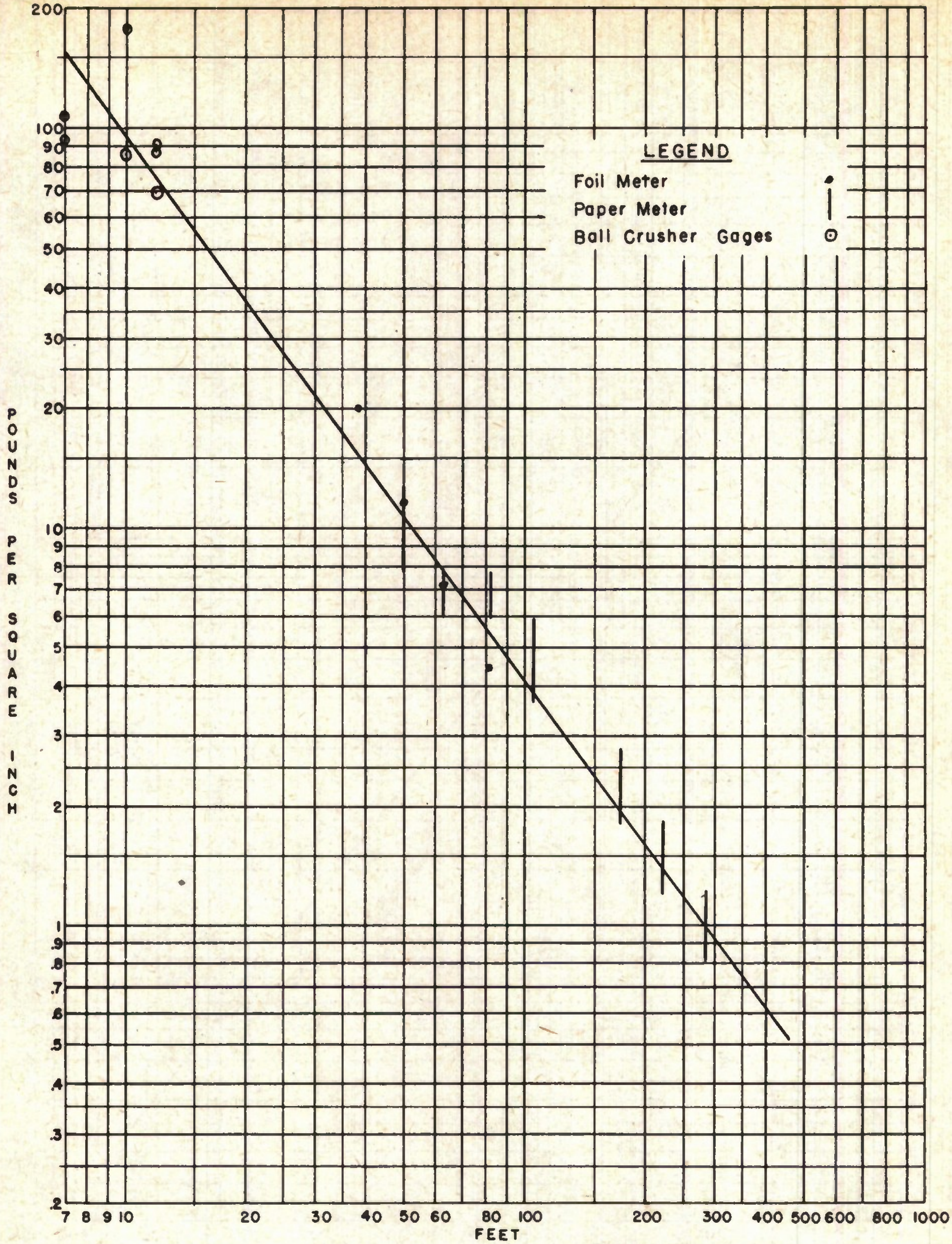


FIG.62A

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No.7 Line No.2&5(Off Sides)

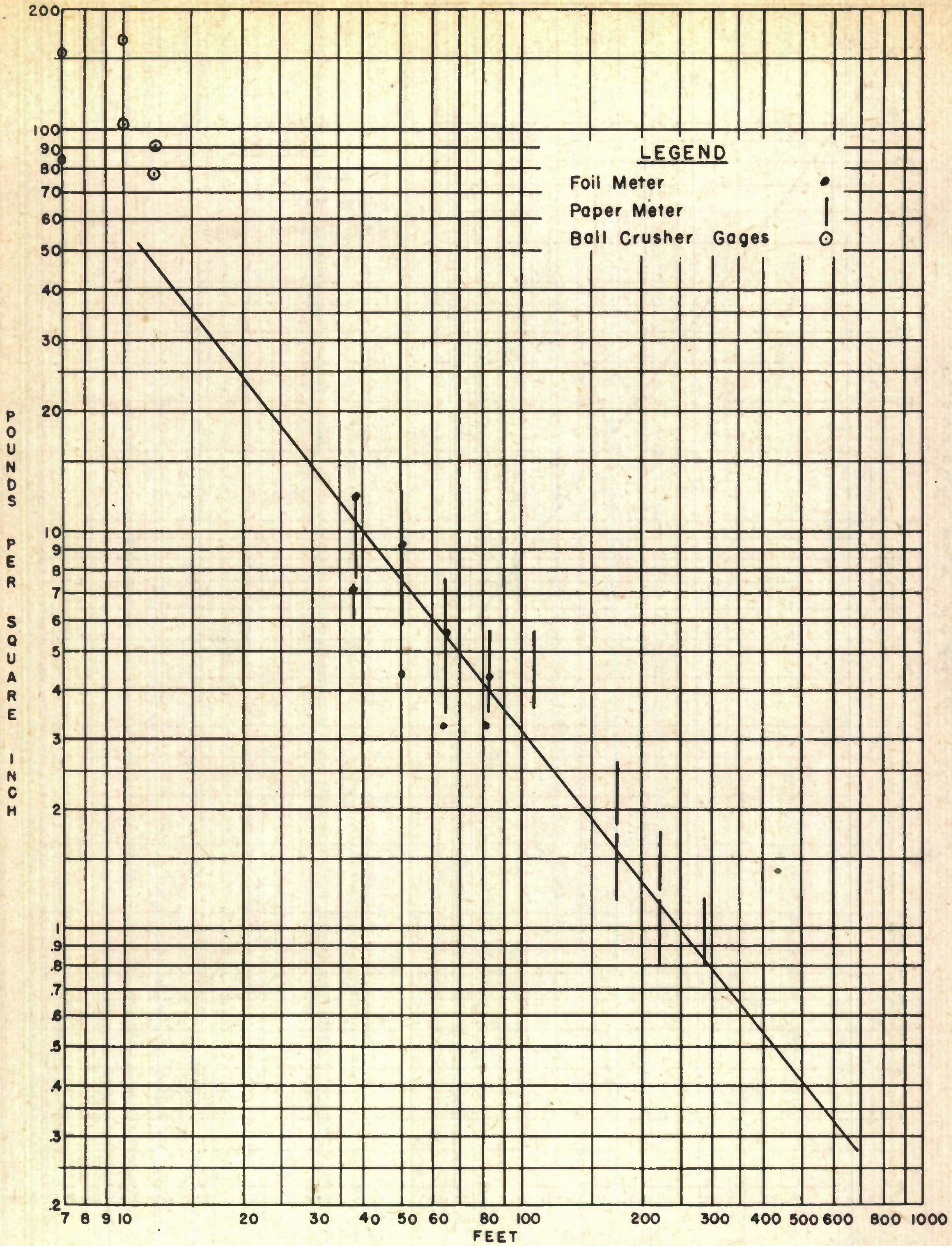


FIG.62B

PEAK BLAST PRESSURE vs. DISTANCE FROM CHARGE

Model Test No. 7 Line No. 1 (Off Ends)

TABLE XX

PEAK BLAST PRESSURES, P. S. I. GAGE, TEST 7

(a) Aberdeen Paper Blast Meters and Plywood Box Foil Meters

Distance from charge (feet)	Paper			Foil		
	Line 1	Line 3	Line 5	Line 1	Line 3	Line 5
38	7.7–12.6	5.8–7.7	>12.6	12.5	7.25	20.0
50	7.7–12.6	5.8–7.7	7.7–12.6	9.4	4.4	11.5
64	5.8– 7.7	3.6–5.8	5.8– 7.7	5.6	3.3	7.25
82	3.6– 5.8	3.6–5.8	5.8– 7.7	4.4	3.3	4.4
106	3.6– 5.8	3.6–5.8	3.6– 5.8	......	......	......
173	1.2– 1.8	1.8–2.7	1.8– 2.7	......	......	......
222	.8– 1.2	1.2–1.8	1.2– 1.8	......	......	......
285	.8– 1.2	.8–1.2	.8– 1.2	......	......	......

(b) Ball Crusher Gages

Meter line	Distance from charge (feet)	Deformation, in. X 10^6	Calibration, in. X 10^6 /lb./in.^{2}	Pressure, lb./in.^{2}
1	7	4,500	28.8	156.2
1	10	3,100	20.8	104.0
1	12	2,800	30.2	92.8
2	7	3,100	28.8	107.7
2	10	2,600	29.8	87.3
2	12	2,700	30.2	89.4
3	7	2,500	28.8	86.8
3	10	5,100	29.8	171.0
3	12	2,400	30.2	79.5
5	7	2,700	28.8	93.8
5	10	5,300	29.8	178.0
5	12	2,100	30.2	69.5
5	12	[1] 12,300	134	91.8

[1] Arco gage.

PART V. DISCUSSION

1. Appearance of explosions.

As observed by eye and recorded on colored moving picture film, there was a marked difference in the appearance of the explosions of the charges in earth-covered igloos and those of open or revetted stacks of bangalore torpedoes. In the former there suddenly appeared relatively small flashes and rapidly expanding plumed bulbous clouds, light brown to dark gray in color, which consisted largely of silt particles from the site; whereas the latter showed brighter flashes and relatively narrow, vertical, bluish-gray smoke columns, skirted with sprays of light brown dust, which mushroomed on reaching maximum height. The difference between the explosions with standard earth cover and those with moderately and heavily increased earth cover was not great, but in the latter case, the smoke and dust clouds seemed to spread out farther laterally and were generally larger. In comparing the shot of the bare stack (Shot 6) with that of the revetted stack (Shot 7), the revetment seemed to have no effect, for as far as the observer could tell, the two explosions looked very much alike. In comparing the 500-pound shots (4 and 5) with the 250-pound igloo shots (1, 2, and 3), the main difference appeared to be a larger and brighter flash from the 500-pound charge as might be expected. The films of the latter shots show the first flash of flame apparently coming out of both ends of the igloo, thus indicating that the end walls were probably blown out first. The smoke and dust clouds from the 500-pound shots were larger, and scaled well with the 250-pound explosions. The air shock wave was not seen by any of the observers and did not appear in the motion pictures, although its presence was disclosed by its effect on the ground, which appeared as an extremely high-velocity wave front of suddenly risen dust and agitated vegetation.

2. Air Blast.

(A) General. Despite the scatter of the data, the average straight lines (on logarithmic paper) representing the pressure vs. distance relations for the several explosions agree quite well and exhibit certain consistent and definite trends; among these are asymmetry in the blast with respect to direction and decrease in blast intensity with increased earth cover. Values obtained in the 500-pound shots are substantially greater than those of the 250-pound series; at 100 feet in front of the primary igloo, the peak pressure was about 5 p.s.i. in the 500-pound test and 3 p.s.i. in the 250-pound test.

(B) Comparison with 1945 Arco and Camp Edwards Tests. In figure 63 peak pressures obtained off the sides of the primary igloo in Tests 1 and 1–A are plotted against reduced distance (distance divided by cube root of charge weight) on logarithmic paper along with the line obtained in the 1945 Arco and the Camp Edwards tests, as reported by reference 4, part VII. Through the center of the coincident range the two lines agree closely but as the slopes are not the same there is divergence near the ends. (The slope of the line drawn for these model tests is determined from data over a greater range of distances.) However, it appears that there is sufficiently close agreement to warrant a statement that the blast pressures followed the model law.

(C) Comparison with Peak Pressure Values Determined from NDRC Nomograph. Chart 3A1 of reference 9, part VII predicts values which agree quite well with those obtained in these tests in the lower ranges of pressure, but are much higher in the upper ranges. This is shown by figure 63, on which the NDRC values for a 250-pound charge are plotted against reduced distance along with the line for Arco model tests 1 and 1–A. The NDRC line is concave upwards rather than a straight line, and indicates pressure increasing at a much greater

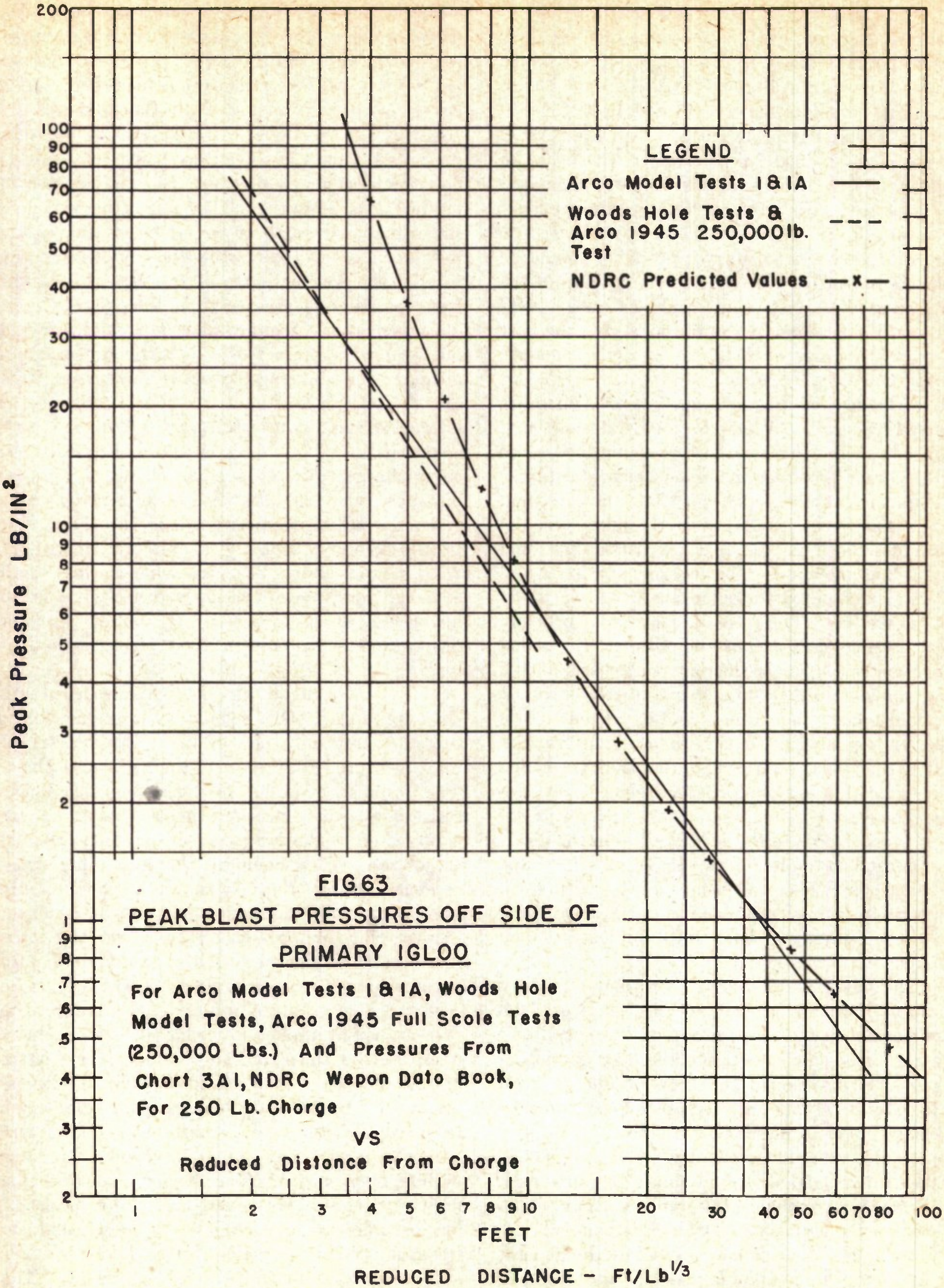


FIG. 63

PEAK BLAST PRESSURES OFF SIDE OF PRIMARY IGLOO

For Arco Model Tests 1 & 1A, Woods Hole Model Tests, Arco 1945 Full Scole Tests (250,000 Lbs.) And Pressures From Chort 3A1, NDRC Wepon Dato Book, For 250 Lb. Chorge

VS

Reduced Distonce From Chorge

rate than linearly (on logarithmic graph paper) as distance decreases. It gives a value of 100 p. s. i. at a distance of 10 feet from a charge of 250 pounds, whereas the values obtained in the Arco and Camp Edwards model tests were of the order of 100 p. s. i. Extrapolated inward to 3 feet, the NDRC curve would indicate a pressure of the order of 400,000 p. s. i. Various authorities have estimated the pressures within the explosive container itself at from 200,000 to 1,500,000 p. s. i., hence the curve for very short distances probably should be concave upward; however, there is nothing in the data from these tests that would indicate curvature, and a straight line appears to give the best fit over the range of distances in which pressure measurements were made.

(D) Asymmetry of Blast. Figure 64, on which are plotted pressure contours for model tests 1 and 1–A, illustrates the asymmetry of blast pressure with respect to direction in the horizontal plane. The maximum pressures occur along the extension of the transverse center-line of the igloo, and the minimum occur to the rear on the longitudinal center-line extended. The pressures in front and off the quarters of the igloo are in between the extreme values. The ratio of side to rear pressure at a distance of 20 feet is about 1.5 to 1. As distance increases, the eccentricity decreases; at 100 feet, the side-to-rear ratio is about 1.4 to 1. At great distances the contours will approach circles. Greater pressure off the side than off the front or rear of the igloo would be expected from the shape of the pile of bangalore torpedoes, since experience has shown that rectangular stacks of high explosives generate greater blast intensities in the direction normal to the long axis. In Test 1, the shape of the crater, which had benched sides with steep faces in front and rear, and comparatively long gouged-out slopes on both sides, indicated much greater lateral pressure.

The fact that pressures were greater directly in front of the igloo than to the rear would be expected in view of the uncovered front wall and the gap between the wall and the door barricade.

(E) Effect of Augmented Earth Cover. The pressure data conclusively show a decrease in blast intensity as earth cover is increased. Figure 65 is a plot of pressures vs. reduced distance for various cover-charge ratios, and figure 66 shows pressure as a function of cover-charge ratio at a constant value of reduced distance, 35 ft./lb.$^{1/3}$. Some of the lines in figure 65 are inconsistent but the general trend seems unmistakable, and in drawing the curves of figure 66 the out-of-line points have been disregarded. Side pressure declines most markedly, while front and rear pressures decrease less rapidly as the earth-cover is increased. At a cover-charge ratio of about 30, the pressures are equal in all directions. Beyond this value, side pressure becomes less than front or rear pressure, and the eccentricity of contours which existed in figure 64 is reversed. This might be expected since increased earth cover offers greater lateral resistance, partially diverting the explosive energy toward the weaker parts of the structure. The front pressure is greater than that to the rear, inasmuch as the front wall is not earth-covered but at most is protected by a barricade across an air-gap. The average pressure decreases from about 1.0 p. s. i. at a cover-charge ratio of 12 (standard earth cover) to about 0.85 p. s. i. at a cover-charge ratio of 4.8. A graph of pressure vs. cover-charge ratio at a small value of reduced distance, such as 3.5, would exhibit the same general relationships between side, front, and rear pressures, and a decrease in pressure from about 25 p. s. i. to about 13 p. s. i. when normal earth cover is quadrupled. At short distances, a given increase in earth cover evidently causes a greater proportionate decrease in blast pressure than at long distances.

It has been shown that augmented earth cover produces: (1) a reduction in average blast pressure, and (2) a change in the asymmetry of blast pressure with respect to the horizontal plane. The latter effect is due to the change in relative resistance with respect to direction as the cover is increased. The former effect may be explained as follows: Work done by the expanding gases is measured by $\int pdv$, where p is the pressure exerted on the surroundings and dv the resulting increase in volume. Earth cover on the igloo increases the value of p at the instant of failure because of compression in the arch which must be removed before failure occurs. After failure, the pressure is not applied immediately to the atmosphere but to the earth cover whose mass offers greater resistance to acceleration than the atmosphere. By the time a given change of volume has been reached, the average pressure and therefore $\int pdv$ is larger than would have been the case with an open charge. This mechanical work done in breaking out of the covered igloo and accelerating the concrete and earth is energy absorbed from the gases and their residual internal energy available to form an air shock wave is lessened. The

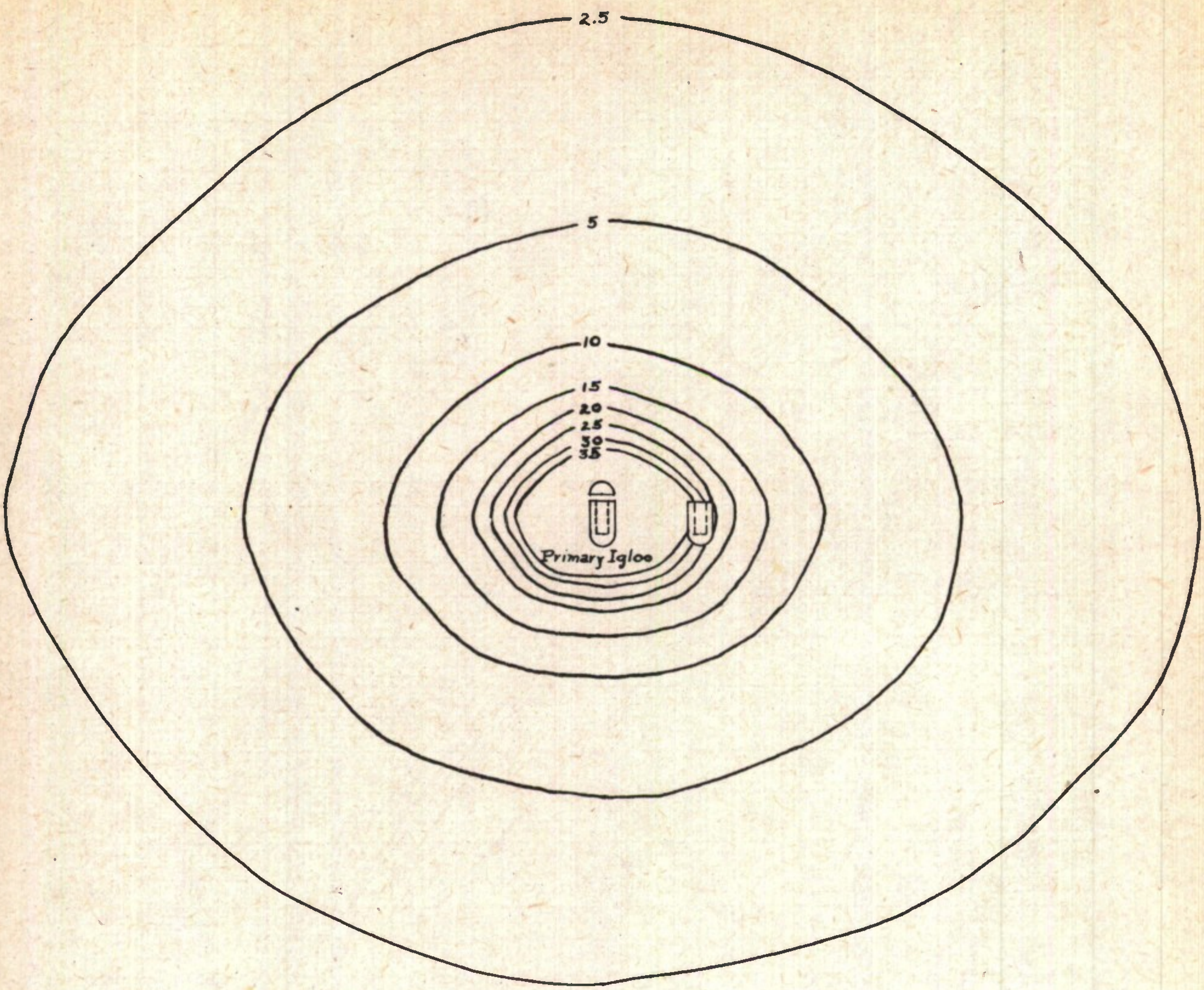


FIG. 64

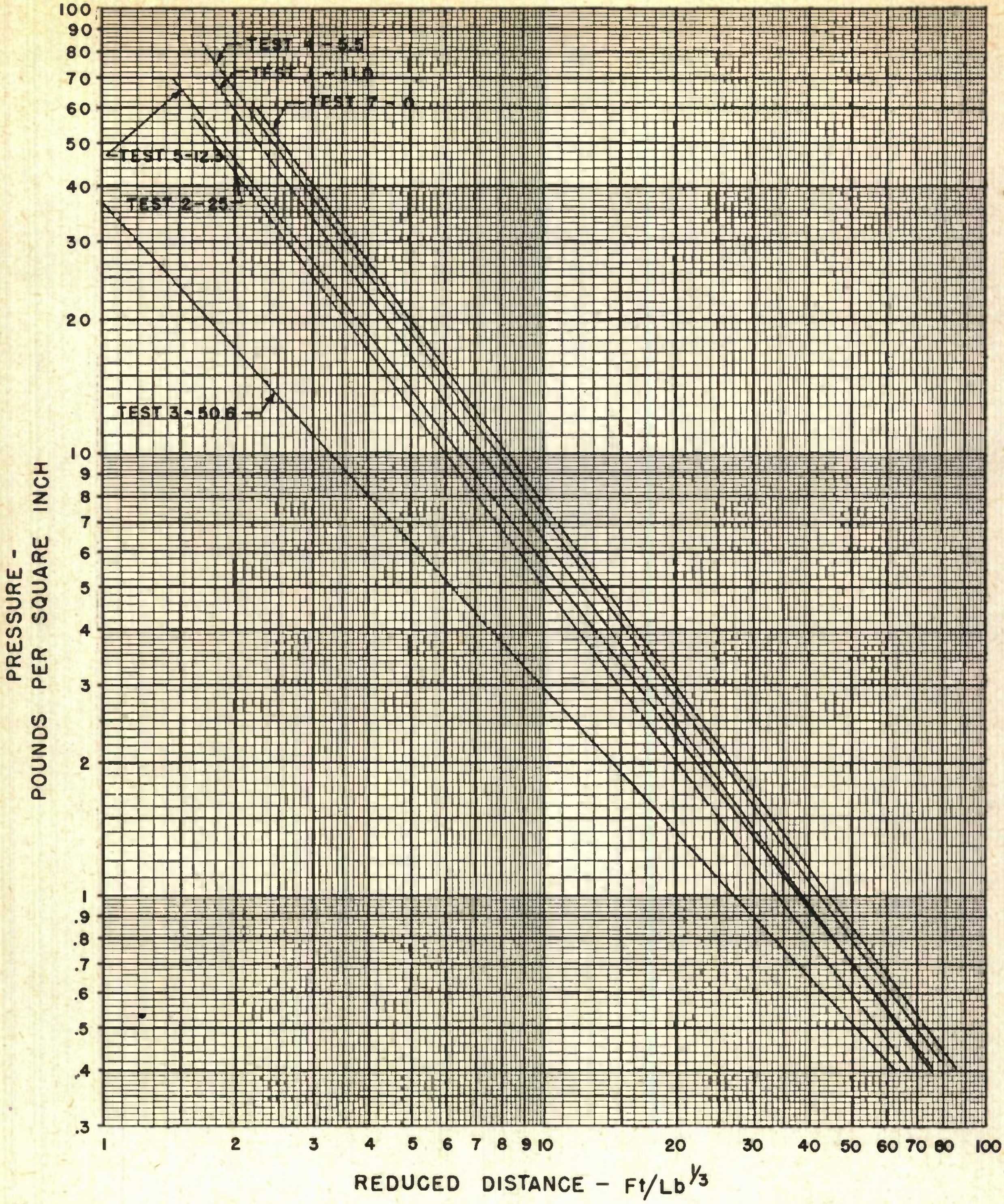
ESTIMATED CONTOURS

PEAK BLAST PRESSURE, P.S.I.

Model Tests 1 & 1A

250 lb. Chg.

scale: 1"=40'



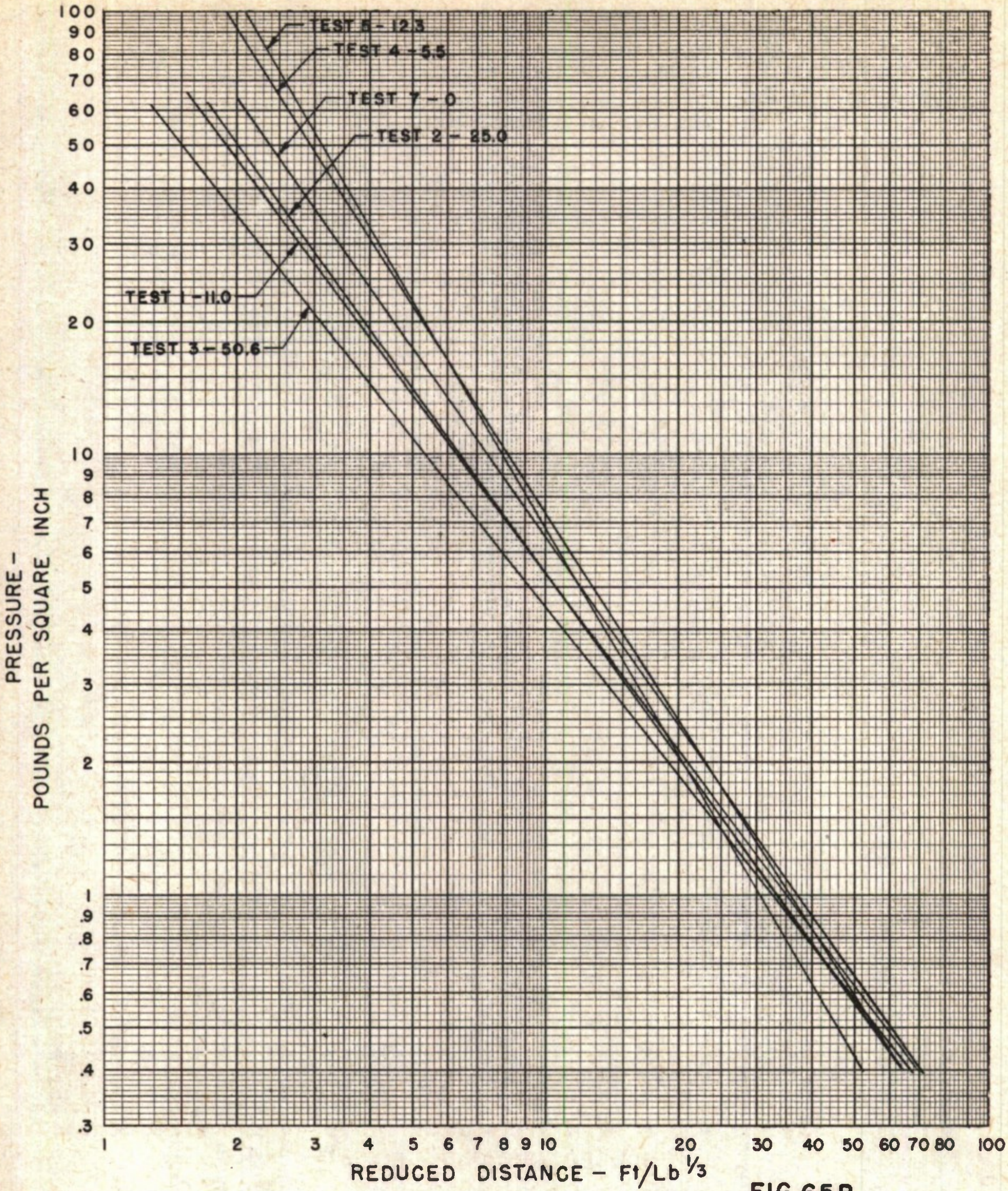
NOTE -

In Legends On Lines, Number Following Test Number Signifies Cover-Charge Ratio.

FIG. 65A

COMPARISON OF PRESSURE vs REDUCED DISTANCE CURVES FOR VARIOUS COVER-CHARGE RATIOS

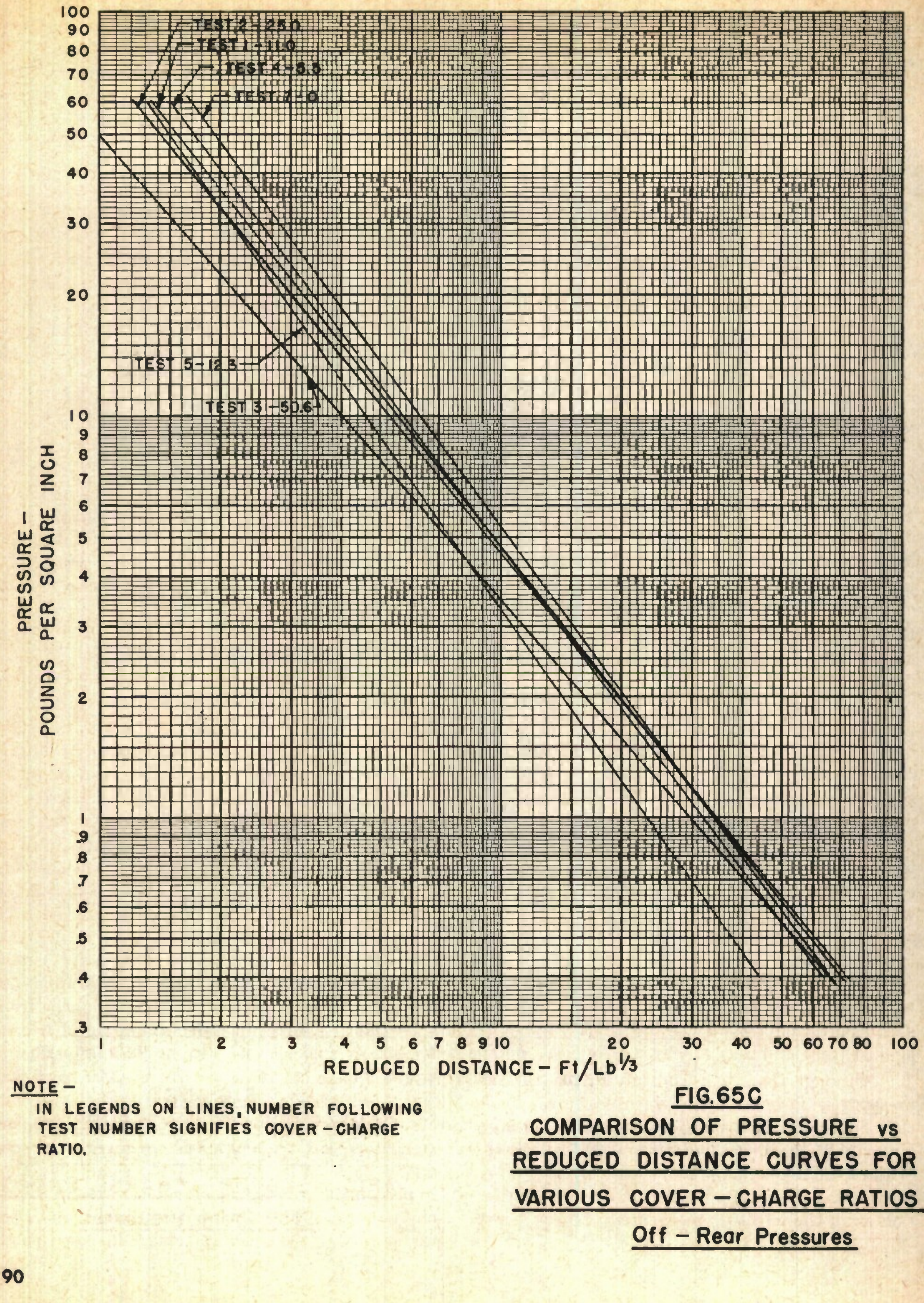
Off-Side Pressures



NOTE -

IN LEGENDS ON LINES, NUMBER FOLLOWING TEST NUMBER SIGNIFIES COVER-CHARGE RATIO.

FIG. 65B
COMPARISON OF PRESSURE vs REDUCED DISTANCE CURVES FOR VARIOUS COVER - CHARGE RATIOS
Off - Front Pressures



NOTE -

IN LEGENDS ON LINES, NUMBER FOLLOWING TEST NUMBER SIGNIFIES COVER - CHARGE RATIO.

FIG. 65C

COMPARISON OF PRESSURE vs REDUCED DISTANCE CURVES FOR VARIOUS COVER - CHARGE RATIOS

Off - Rear Pressures

greater part of the absorbed energy appears in the form of kinetic energy of the accelerated solid matter. Large fragments of metal casing and concrete may fly far enough to cause damage but the soil (unless it contains gravel or rocks) merely forms a dust cloud whose particles rapidly lose their velocity through air resistance and gravity and settle harmlessly to the earth. The proportion of energy absorbed by earth cover may be large; for example, if a 250-pound charge detonated in a model igloo covered with earth weighing 10,000 pounds produces a mean maximum particle velocity of 1,000 feet per second, the kinetic energy of the accelerated earth would be $\frac{1}{2}\times\frac{10,000}{32.2}\times(1,000)^2=155\times10^6$ foot-pounds. This would be about 40 percent of the theoretical total energy available in the charge, which is about 380×10^6 foot-pounds.[1] Presumably the percentage absorption is non-linear with increase in earth cover as mean maximum velocities probably decrease. This appears to be the case inasmuch as the pressure vs. cover-charge ratio curves, figure 66, are concave upward, showing less benefit derived from a given increment as total cover is increased.

From the above considerations it appears that the efficacy of earth cover as an explosion energy absorber is a function of its quantity, density, and configuration. Increase in quantity or density will increase the work done by the gases and hence the absorbed energy. An optimum configuration of cover will both reduce asymmetry of blast and extract more work by requiring the explosion gases to act on the resisting earth through greater distances, resulting in greater product of force times distance and greater mean maximum particle velocity hence greater kinetic energy of the earth. The optimum configuration would be that whose cross-sections had the least polar moment of inertia for a given area, that is, the one having the most earth closest to the charge. The ideal (though impracticable) shape of cover on an igloo would probably have an outer surface following a concentric circle and equally thick earth-walls against front and rear.

Although these tests indicate that peak blast pressure is lowered by augmented earth cover, they do not indicate the effect on positive impulse. Unfortunately, it was not within the capabilities of the available equipment to take impulse measurements. However, in the absence of information as to the effect of augmented earth cover on the duration of the positive phase of the blast wave, one would presume that the impulse which is the integral of pressure with respect to time, would decrease in proportion to the peak pressure. It is recognized that a full appraisal of the ability to cause damage of an air blast wave cannot be made without knowledge of the impulse.

(F) Evaluation of Earth Cover in Reducing Safety Distances. It has long been customary to decrease safety distances between stored high explosives and inhabited buildings by 50 percent when the explosives were "barricaded." However, a clear-cut definition of what constitutes a barricade never seems to have been given. The Army and Navy have arbitrarily considered that an earth-covered igloo constituted an effectively barricaded storage, and consequently have halved the inhabited building safety distances prescribed by the American Table of Distances whenever earth covered igloos were used. The 1945 Arco test showed that the halved distance is not adequate to prevent considerable flying glass, superficial damage and minor structural damage in a frame dwelling, indicating that a reconsideration of the efficacy of the earth-covered igloo in reducing blast was in order.

It is believed that figures 65 and 66 offer a clue to a more rational evaluation of the effect of earth cover which, when corroborated by more complete and accurately instrumented investigations may enable future selection of safety distances on the basis of closely known reduction in ability to cause damage for a given quantity of explosives placed in a given earth barricaded or covered storage. From the information given in figures 65 and 66, and from the model law, a graph has been constructed (figure 67) showing peak pressure off the side of the exploding igloo as a function of distance simultaneously for various charge weights from 50,000 to 500,000 pounds, and for 250,000 pounds under earth-covered igloos with cover-charge ratios up to 50. (These curves have been adjusted slightly from those plotted direct in order to get rid of irregularities in spacing and slope. The adjustments were all made in a direction to give more conservative results.) The curves show that, for a constant distance, a considerable decrease in quantity from a 250,000-pound uncovered charge would be necessary to effect the same reduction in peak blast pressure as a given increase in cover-charge ratio or a 250,000-pound charge; and also, for a constant pressure, placing additional earth

[1] Determined from the heat of explosion of TNT, 1080 cal./g.

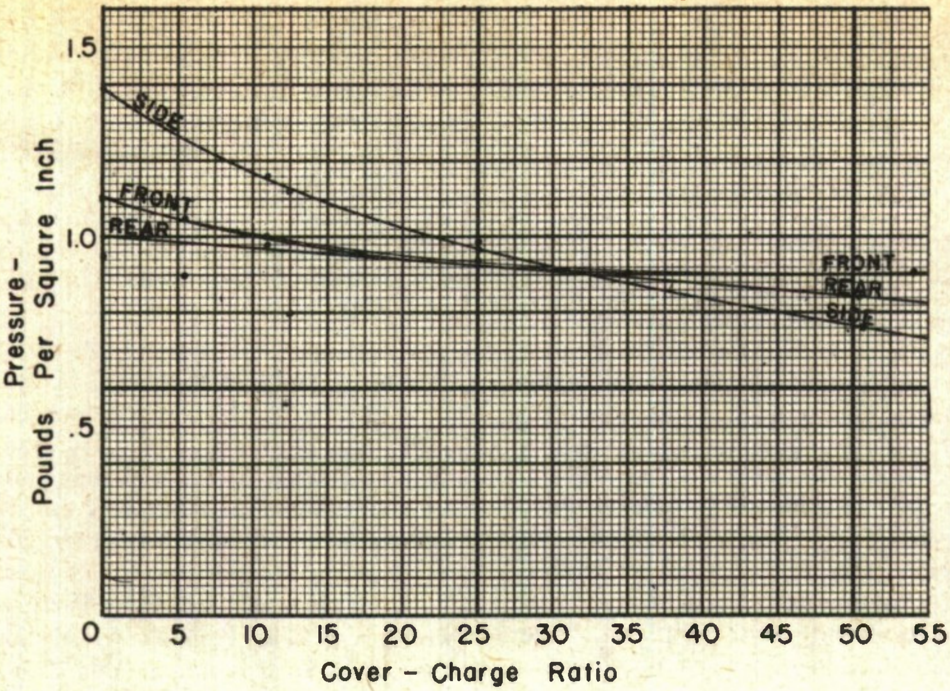
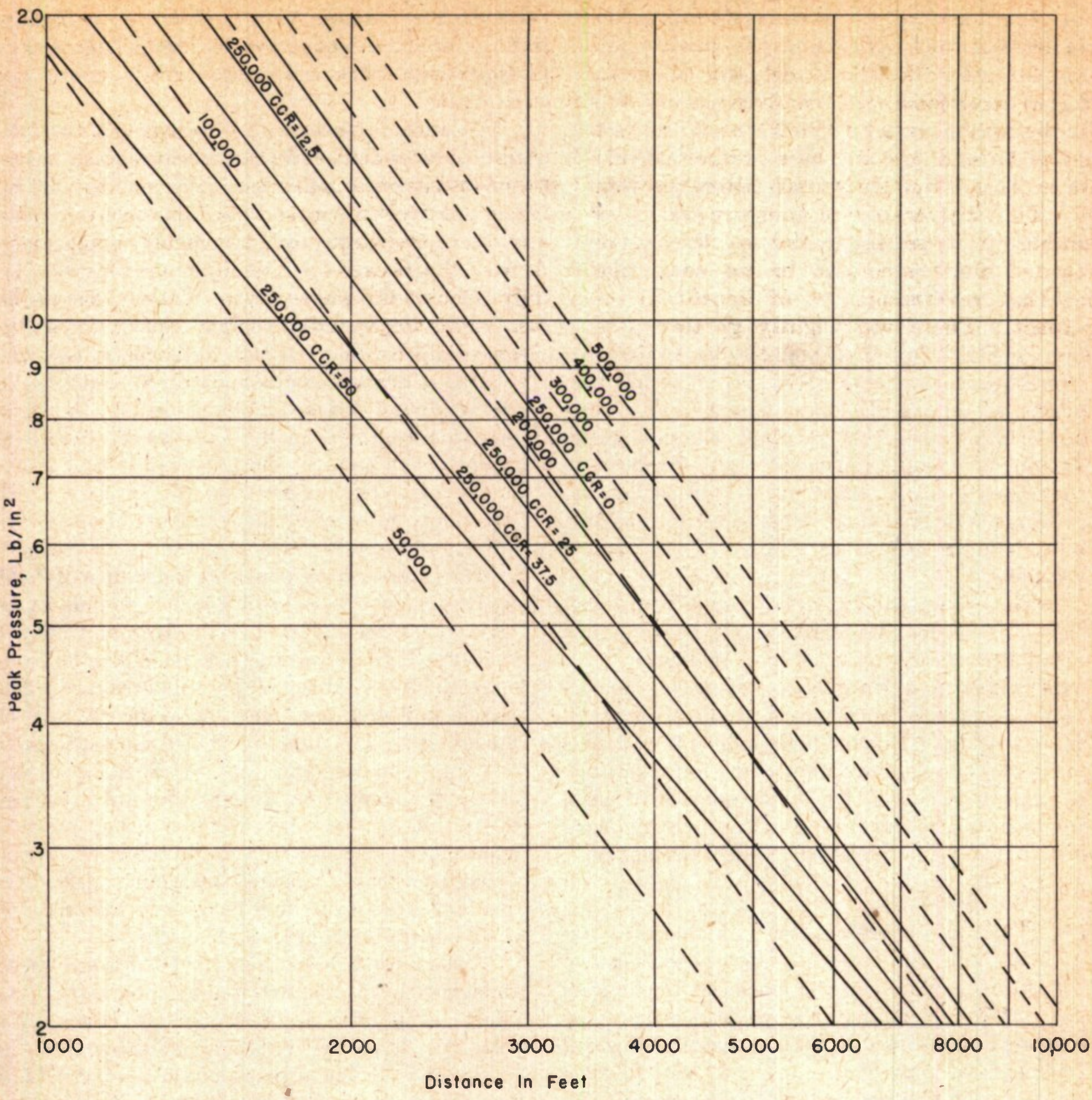


FIG. 66
BLAST PRESSURE Vs COVER-CHARGE RATIO FOR A REDUCED DISTANCE OF 35 FT./LB.$^{1/3}$

cover on an igloo containing a 250,000-pound charge is equivalent to moving closer to a reduced charge. For example, at a distance of 4,310 feet (the unbarricaded inhabited building distance prescribed by the American Table of Distances) a 250,000-pound charge with no cover gives about 0.5 p. s. i. If the charge is detonated inside a standard igloo (cover-charge ratio of about 12.5) the pressure is reduced to about 0.45 p. s. i.; this is equivalent to reducing an uncovered charge to about 200,000 pounds. If the cover-charge ratio were about 43, one would have to move in to about 3,200 feet to get the original pressure (0.5 p. s. i.); this pressure would be produced by an open charge of about 100,000 pounds at that distance. Charts similar to figure 67, developed from corroborating experiments with full-scale charges and providing for off-front and off-rear as well as off-side pressures for various charge weights, could be used to select safety distances for any ordinary condition of igloo storage, provided constant peak pressure is utilized as the criterion for constant degree of damage. For example, figure 67 indicates that placing a 250,000-pound charge in a standard igloo would warrant a decrease from the A. T. D. specified distance of 4,310 feet to about 4,000 feet, or to a distance specified as safe from a charge of about 200,000 pounds, which according to the A. T. D. is 4,060 feet. The distance could not be halved (to 2,155 feet) unless the cover-charge ratio were raised to nearly 100, or the charge reduced to about 30,000 pounds (for which the A. T. D. distance is 2,260 feet).

Inasmuch as peak pressure alone is not the true criterion for damage, charts actually developed for this purpose should take into account the effect of impulse, which results in the same degree of damage at lower peak pressures when charge weights are increased.

It is emphasized that the foregoing pressures and distances are approximate, and are derived by up-scaling the results of the model tests. Figure 67 is not recommended for actual use, but it qualitatively illustrates trends which are believed to exist. Further studies should be



LEGEND

— — —	Open Charges
———	Covered Charges
CCR	Cover-Charge Ratio

FIG. 67

PEAK BLAST PRESSURE Vs DISTANCE FROM CENTER OF CHARGE ON TRANSVERSE IGLOO AXIS EXTENDED, For 250,000 Lbs. Of H.E. With Various Cover Charge Ratios & For Various Other Charge Weights In Similar Rectangular Stacks In The Open.

made on the basis of full-scale tests in which inaccuracies due to the failure of gravity to scale and other defects of the model tests will not exist.

(G) Effect of Revetments. A comparison of the pressure-distance curves for Tests 6 and 7 in part IV (figures 58 and 62) indicates greater off-side pressure in Test 7 but greater off-end pressure in Test 6. The scatter of the pressure values is considerable in these tests, and as they were not repeated there seems to be no conclusive evidence that revetments are of benefit in reducing blast. There was slightly greater glass breakage in Test 7, which seems to indicate higher pressure values. However, it is felt that additional data should be obtained from a series of tests of open vs. revetted charges before drawing a definite conclusion. On the basis of the present data, all that can safely be said is that revetments may reduce blast pressure slightly, but not sufficiently to warrant reduction in safety distances.

There is considerable earth in a revetment, the 30- by 60-foot standard Army type containing about 680 cubic yards as compared with 1,100 cubic yards on a Navy igloo. However, the revetment earth is not disposed as effectively as in the case of the igloo (the polar moments of inertia of its cross-sections are very high) for absorption of explosion energy. The same amount of earth would be a great deal more effective in reducing blast if it were piled directly on top of the charge.

3. Glass Breakage.

(A) Shot 1 vs. 1945 Arco Test. In the 1945 test with the full-scale barracks, most of the glass in the glazed face nearest the explosion (making an angle of 30° to the line from the explosion) "was shattered with sufficient force to scatter it in small fragments over the entire floor area and in some cases to drive the fragments into the columns and into the far wall . . . The flying glass would have presented a distinct hazard to anyone occupying the building . . ." The report (reference 3, part VII) indicates that 80 of the 90 panes of double-strength, B quality glass, measuring approximately 38 by 15 inches, on this elevation, or 89 percent, were broken. The breakage in the model test simulating the full-scale test, Shot 1, was much less. No breakage at all occurred in the 30° panel (corresponding to the barracks elevation mentioned above), and only one pane broke in each of the 60° and 90° panels. Furthermore, there was no "flying glass"; the fragments were not driven through the frames, but fell almost vertically, most of them landing on the front edge of the platform on the side of the panels *nearest* the explosion.

Variance between the breakage in the full-scale test and that of the model test was anticipated, although it had been believed that the incidence of broken panes, if not their behavior subsequent to fracture, would be roughly comparable. Among the causes for the difference may be (1) diffraction of the pressure wave behind the panels resulting in decreased net effective pressure on the glass, which could not have occurred in the full-scale test wherein the windows were mounted in the wall of an enclosed building, and (2) the effect of positive impulse in the blast wave, which was ten times as great in the full-scale test as in the model test. The major cause was the first, which was shown to be so by a comparison of open-back and enclosed-back panels in the full-scale test program. In open-back panels at a distance of 2,705 feet from an explosion of 250,000 pounds in an igloo with twice standard earth cover, no glass was broken. In an enclosed-back panel at the same spot, there was about 50 percent breakage. The panels were the same ones that were used in the model tests. The dimensions of these panels were evidently small enough that the shock wave was able to propagate from the edges toward the center of the back and exert compensating pressure against the panes from the rear in the brief interval before the panes reached maximum deflection. The deflection time may have been increased by the resiliency of the panels themselves.

The second reason may have had some effect, though such was not disclosed by these tests. The effect of impulse is illustrated by Chart 6A4, reference 9, part VII, which indicates that the radius of breakage of panes of glass is not a function of (charge weight)$^{1/3}$ but of (charge weight)^n, where n is about 0.37 for 11- by 14- by 0.12-inch panes and increases with pane size, being about 0.59 for 48 -by 48- by 0.12-inch panes. Since peak blast pressure is equal at distances which are a function of (charge weight)$^{1/3}$, it is apparent that glass breakage, particularly of the larger sizes, is not governed by peak blast pressure alone. Positive impulse, which is equal at distances proportional to (charge weight)$^{2/3}$, has an effect. As pane size increases, n approaches $2/3$, which is the limiting value for large thick sheets such as heavy plate and structural glass panels of low natural vibration frequency.

The relatively greater impulse time in the full-scale tests is believed to account for the flying glass in these tests which did not occur in the model tests. Subsequent to fracture, the fragments of glass were still subjected to pressure which propelled them into the interior of the building at considerable velocity in the full-scale tests. In the model tests, the pressure reached zero and became negative relatively much sooner, causing the fragments to fall vertically or to be sucked back through the window opening and fall out toward the explosion.

(B) Shot 4 vs. 1946 Arco Test. In the 1946 test with a detonation of 500,000 pounds of TNT in an igloo 2,705 feet from the first barracks, 3,605 from the second, and 5,410 from the third, the breakage in the two elevations most nearly toward the blast was approximately as follows: Barracks 1: 38- by 15-inch panes, 100 percent; 15- by 12-inch panes, 30 percent; 10- by 9-inch panes, 0 percent; Barracks 2: 38- by 15-inch panes, 23 percent; 15- by 12-inch panes, 7 percent; 10- by 9-inch panes, 0 percent; Barracks 3: 38- by 15-inch panes, 0 percent; 15- by 12-inch panes, 0 percent; 10- by 19-inch panes, 0 percent. This breakage is again considerably greater than that experienced in the corresponding model test, in which there was only 33 percent breakage of 38- by 15-inch panes at 270.5 feet and no other breakage whatsoever. Here again, there was flying glass in the full-scale test whereas in the model test the fragments dropped almost vertically, the greater proportion falling on the side nearest the explosion.

(C) Breakage Correlated with Peak Blast Pressure. Although it is considered that the true criterion for glass breakage is neither peak blast pressure nor impulse, but is the pressure-time characteristic from the instant of impingement of the shock wave until the pane has reached its critical deflection, the peak pressure value is of predominant importance, and it may be of interest to compare the breakages on the basis of peak pressure alone. The breakages are tabulated together with corresponding pressures in table XXI.

TABLE XXI

GLASS BREAKAGE VS. CORRESPONDING PEAK PRESSURES

Test No.	38- by 15-inch panes											
	Panel 1				Panel 2				Panel 3			
	Pressure, p. s. i.	No. Broken			Pressure, p. s. i.	No. Broken			Pressure, p. s. i.	No. Broken		
		30°	60°	90°		30°	60°	90°		30°	60°	90°
1	1.05	0	1	1	0.74	0	0	0	0.43	0	0	0
2	.98	0	0	1	.72	0	0	1	.43	0	0	0
3	.87	0	0	1	.64	0	0	0	.39	0	0	0
4	.92	0	1	1	.62	0	0	0	.36	0	0	0
5	.60	0	0	1	.39	0	0	0	.23	0	0	0
6	2.8	2	2	2	1.7	1	1	2	1.2	0	0	1
7	1.6	2	2	2	.94	1	2	2	.66	0	0	2
	12- by 15-inch panes											
6	2.8	2	3	3	1.7	0	0	1	1.2	0	0	0
7	1.6	2	3	3	.94	0	0	2	.66	0	0	0
	9- by 10-inch panes											
6	2.8	0	0	0	1.7	0	0	0	1.2	0	0	0
7	1.6	0	0	1	.94	0	0	4	.66	0	0	0

The average peak pressure causing 50 percent incidence of breakage of the 38- by 15- by 0.12-inch panes in the "face on" (90°) panels was 0.89 p. s. i.; for the 12- by 15- by 0.12-inch panes, the estimated value is 1.3 p. s. i. Since the number of tests was so limited, these figures are but rough approximations. Furthermore, these pressures would apply only to unenclosed glass panels and not to windows in buildings.

(D) Effect of Augmented Earth Cover. Inasmuch as greater weight of earth on the igloos resulted in decreased blast pressure, glass breakage was also reduced. Breakage of the 38- by 15-inch panes for various cover-charge ratios are given below:

TABLE XXII

GLASS BREAKAGE VS. COVER-CHARGE RATIO

Shot No.	Cover-charge ratio	Distance of panel from charge divided by cube root of charge weight ft./lb.$^{1/3}$	Number of broken 38- by 15-inch DS panes in panels at 3 angles of orientation		
			90°	60°	30°
7	0 (bare stack)	22.9	2	2	2
		34.1	2	2	1
		45.5	2	0	0
6	6.1 (revetment)	22.9	2	2	2
		34.1	2	1	1
		45.5	1	0	0
4	5.5	34.1	1	1	0
		45.5	0	0	0
		68.2	0	0	0
1	11.0	34.1	1	1	0
		45.5	0	0	0
		68.4	0	0	0
5	12.3	34.1	1	0	0
		45.5	0	0	0
		68.2	0	0	0
2	25.0	34.1	1	0	0
		45.5	1	0	0
		68.4	0	0	0
3	50.6	34.1	1	0	0
		45.5	0	0	0
		68.4	0	0	0

To show the effect of increased earth cover, comparison should be made of the number of panes broken in panels at corresponding values of distance divided by cube root of charge weight, for various cover-charge ratios. For example, in Test 7 with a cover-charge ratio of 0, 5 panes were broken at $d/w^{1/3}=34.1$; in Test 1, with a cover-charge ratio of 11, 2 panes were broken; and in Test 3, with a cover-charge ratio of 50.6, 1 pane was broken.

(E) Effect of Orientation. Table XXII clearly illustrates the fact that for angles of incidence less than 90°, the effective blast pressure and consequent window breakage is reduced. This would not be true, however, were the orientation and dimensional relationship such as to permit formation of a mach reflection. At the distance at which glass test panel assembly No. 1 was located (215 feet) the critical angle of incidence below which mach reflection would occur is approximately 27½° (determined from Section 3A7, reference 9, part VII).

(F) Effect of Pane Size. The greater strength of small panes is well illustrated by a comparison of the glass breakage record sheets. Of the three pane sizes (38- by 15-inch, 12- by 15-inch, 9- by 10-inch), only the largest suffered breakage until Shots 6 and 7. In Shot 6, 11 large, 9 medium, and no small panes broke. In Shot 7, 13 large, 10 medium, and 5 small panes broke. If the total number of each size broken in all the tests is expressed as a percentage of the total number of exposures of each size in all the tests, the following values are obtained: Large, 25.4 percent; medium, 1.06 percent; small, 1.98 percent. One relatively economical method of increasing the protection afforded occupants of buildings from the effects of a possible explosion is by subdividing windows into small panes without decreasing pane thickness as is normally done (common practise is to use single strength glass for widths less than 24 inches). When thus increasing the blast resistance of the glass, however, proportionate strength must be provided in muntins, sash rails, and frames, in order to preclude structural failure which would nullify the benefit of stronger glazing.

(G) Validity of Model Tests in Predicting Breakage in Full-Scale Tests. These tests were not true model tests so far as the glass was concerned, for the panels were not scale models of windows in the full-scale program, but rather contained full-size panes of glass exposed to the same peak blast pressure as in the full-scale program. As has already been pointed out, breakage of glass in these test panels bears little relation to window breakage in the full-scale barracks owing to (1) the diffraction of blast pressure behind the open-back panels, and (2) the differences in pressure-time characteristics of blast waves from detonations of large and small charges. If the test panels had been enclosed in the rear, much of the discrepancy in breakage would have been removed, but the distances would have had to be proportional to about (charge weight)$^{0.4}$ rather than (charge weight)$^{1/3}$ for 38- by 15-inch panes (and to different distances for the other two sizes of panes) for more faithful reproduction of breakage. For example, had a closed-back panel been placed at a distance of $2{,}155\left(\frac{250}{250{,}000}\right)^{0.4} = 136$ feet rather than at 215 feet, the breakage should have agreed well with that experienced in the barracks in the 1945 test wherein 250,000 pounds of TNT was detonated.

True scale models of window panes homologously mounted and situated with respect to model explosions would have periods of vibration in the same ratio to the duration of the positive phase of the blast wave as prototype windows in full-scale explosions. Consequently, breakage of true scale model windows would be expected to reproduce closely that of their prototypes.

4. Fragmentation.

The 250-pound explosions under earth-covered igloos produced relatively few fragments of concrete outside the immediate vicinity of the crater. The size of particles decreased rapidly with distance, and whereas rather large sections of floor slab, up to 12 inches long, were encountered in the crater, no pieces of concrete whatsoever could be found beyond a distance of about 150 feet, and the dust on the ground within this range was pock-marked with holes caused by tiny pieces of concrete and aggregate raining down on it. A few pieces of wire mesh reinforcing were also found in and relatively near the crater. Pieces of bangalore torpedo casing were scattered over a much wider area, the farthest found being at a distance of approximately 400 feet. In this extreme missile range as well as in the general character and distribution of the fragments, the first model test scaled remarkably well with the 250,000-pound explosion of igloo A in 1945 as described in reference 3, part VII, in which relatively large sections of the concrete foundations were found in the crater, and the greatest range for fragments of bomb casing was about 4,000 feet.

From the observations made it could not be said that augmented earth cover had any particular effect on missile distribution; certainly the scene in and around the crater did not change its character in any marked way in the second and third tests, and the scattering of bangalore torpedo casing was about the same. A more detailed survey and preparation of missile maps may have

disclosed a decrease in extreme range, which probably did occur.

The 500-pound explosions produced more perfect demolition of the primary igloos in that no large sections of concrete could be found even in the crater, the largest found being of the order of 2 to 4 inches in largest dimension. In casing fragments the 500-pound series was similar to the 250-pound series, except that the extreme range appeared greater, as the farthest piece found was approximately 500 feet from the crater.

The detonations of revetted and open stacks propelled pieces of bangalore casing to approximately 400 feet. Fewer pieces seemed in evidence than in the igloo explosions, and those found near the crater were larger. It looked as if the lack of cover permitted the tubing to break up into and remain in larger sections.

The extreme missile range for explosions of GP bombs in earth-covered igloos, based on the experience of the 1945 full-scale test (igloo A) and the 1946 model tests, may be represented approximately by the formula

$$R=64\sqrt[3]{W}$$

where R is range in feet and W is net charge weight in pounds. This range is likely to be affected by charge-to-weight ratio of the bombs, amount of earth cover on the magazines, barricading, and configuration of the stack. At this range, the probability of being struck is extremely small, but the probability increases with (roughly) the square of any distance moved toward the explosion. The safe distance prescribed by the American Table of Distances for protection of inhabited buildings from blast (unbarricaded basis) may be roughly approximated by

$$D=69\sqrt[3]{W}$$

(where D is distance in feet) which is somewhat greater, which shows that a structure at the unbarricaded ATD distance is safe from missiles projected from an explosion of bombs in an earth-covered igloo. Explosions of other types of ammunition, particularly rockets, and explosions in other surroundings may project large missiles to greater ranges, however. A structure at the *barricaded* ATD distance stands a good chance of being struck.

5. Cratering.

(A) Comparison of Crater Sizes with Those Obtained by Formula. (1) Volumes. Reference 10, part VII, gives the formula $v=0.4q^{1.14}$ where v is volume in cubic feet and q charge weight in pounds, for predicted volumes of craters from detonations of "brisant commercial dynamite on average soil." For calculating crater volumes when the dimensions are known, it gives the formula $v=0.329d^2h$ (where d is diameter and h apparent depth). Values obtained from these formulas are compared with the actual crater volumes obtained in these tests in the following tabulation:

TABLE XXIII
CRATER SIZES FROM FORMULAS VS. ACTUAL CRATERS

Test	Charge weight, (pounds)	Crater volumes, cu. ft. Predicted by $.4q^{1.14}$	Calculated by $.329d^2h$	Actual volume of apparent crater
1	250	217	173	110
1-A	250	217	132	125
2	250	217	142	163
3	250	217	191	108
4	500	477	288	381
5	500	477	279	218
6	250	217	74	81
7	250	217	81	84

It is seen that the predicted values do not agree with the actual values, but that the values calculated by $.329d^2h$ average fairly close to the actual volumes. However, as the latter formula does not fit very well in individual cases, it is believed to be better practise to determine a given crater volume by survey, cross-sectioning, and use of the average end-area method as is normally done in earthwork computations, rather than to depend on an empirical formula to determine such an erratic quantity.

It would be possible to find new constants for the formula for predicted volumes in the form $v=kq^n$ from the above data, but it is felt that the paucity of the data would render this hardly worth while.

(2) Diameters. The crater diameters obtained may be compared with those computed by formulas from various authorities:

Authority	Crater diameter, feet	
	250 lbs. H. E.	500 lbs. H. E.
NDRC Weapon Data, Chart 3B1a, Reference 9, part VII (chart read for charge at zero depth below ground surface)	22	28
British formula, $d=\frac{8}{3}Q^{1/3}$ (where d=diameter in feet, Q=charge weight in pounds)	16.8	21.2
French formula, $r=0.5p^{1/3}$, (r= radius in meters, p=charge in kilograms)	15.9	20.0
Formula from Capt. E. R. Gayler, CEC, USN (Ret.) $d=2.5Q^{1/3}$	15.8	19.8
Olsen formula $R=0.69Q^{4/9}$ (R= radius in feet, Q=charge in pounds)	16.0	21.8

The NDRC values appear out of line. The chart from which they were taken was designed primarily for determination of crater dimensions from bombs exploding after penetrating the ground to various depths, and appears to give values for zero depth only incidentally. This chart also gives values of apparent crater depth, which for 250 pounds is 5 feet and for 500 pounds 8 feet; these figures are far greater than the depths experienced in these tests.

The average of the diameters determined by the last four formulas, which agree quite well among themselves, are 16.1 and 20.7 feet, respectively, for 250- and 500-pound charges.

These values do not compare as closely as might be expected with averages of the apparent diameters obtained in the Camp Edwards and Arco igloo shots, which were 14.8 and 18.2 feet, respectively, for 250- and 500-pound charges. It is possible that the formulas refer to true diameters instead of apparent diameters except in the case of the NDRC formula which is known to apply to apparent diameters. Since apparent diameters are more conveniently and accurately determined, true diameters were not obtained in the model tests, but they would probably be about a foot greater than the apparent values, in which case they would agree fairly well with the formulas. The diameters obtained in the two open shots, that is, with revetted and unprotected 250-pound charges, strangely are much less and do not agree with the formulas at all. The average value in this case was only 10.7 feet.

(B) Comparison with Craters Obtained in 1945 Arco and Camp Edwards Tests. Data obtained on craters in these tests and the previous Board tests are tabulated in table XXIV.

(C) Effect of Difference in Soils at Arco and Camp Edwards. There is no significant difference between the apparent crater diameters of Camp Edwards Tests 1 and 2 and those of Arco Tests 1 and 1–A. Apparent depths, however, average 50 percent greater at Camp Edwards. Evidently diameters are not as greatly affected by variations in soils as depths. A possible explanation of the greater depth at Camp Edwards is that the clay soil, being plastic and cohesive, tends to flow under stress and to cling together in masses, forming steeper sides and sharper irregularities, whereas the dry Arco soil pulverizes to a large extent, forming masses of low cohesion which slide into low spots. In the second Camp Edwards test, there were pockets of sand in which deep holes were blown.

(D) Effect of Augmented Earth Cover on Craters. Neither table XXIV nor figure 68 show any consistent tendency of increased earth cover on igloos to affect the crater diameters, but the table shows a small increase in depth. This is regarded with suspicion in view of the small number of tests. There is a decisive increase of about 40 percent in diameters from explosions within earth-covered igloos as compared with explosions in revetments or in the open, but crater depths are about the same in either case and vary considerably from test to test. Crater volumes when earth-covered igloos are used are considerably greater than volumes obtained from open explosions. These general relationships should hold true in any relatively homogeneous granular soil of sufficient depth over bedrock.

TABLE XXIV

CRATER DATA

Test	Charge (pounds)	Explosive	Shelter	Approximate cover-charge ratio	Apparent crater diameter (feet)	Apparent crater depth (feet)	$\frac{d}{W^{1/3}}$*
Arco No. 1	250,000	50–50 amatol	Igloo	12	175	8	2.78
Arco No. 2	125,000	do	Revetment	14.7	81	7.7	1.62
Arco No. 3	250,000	Torpex	Igloo	12	142	16	2.25
Arco No. 5	250,000	do	do	12	146	12	2.32
Arco No. 6	125,000	50–50 amatol	Revetment	14.7	88	10.4	1.76
Arco No. 7	250,000	Amatol and others	None	0	110	2.4	1.75
Arco No. 8	250,000	TNT	do	0	112	14.9	1.78
Camp Edwards No. 1	250	80–20 amatol	Igloo	12	14.5	2.5	2.30
Camp Edwards No. 2	250	do	do	12	15	3.6	2.38
Camp Edwards No. 3	250	do	None	0	[1] 16.2	3.0	2.57
Camp Edwards No. 4	250	do	do	0	[1] 16.9	3.0	2.57
Camp Edwards No. 5	250	do	Revetment	7.3	[1] 17.0	3.5	2.70
Arco Model No. 1	250	do	Igloo	11.0	15.8	2.1	2.51
Arco Model No. 1–A	250	do	do	11.0	14.5	2.0	2.30
Arco Model No. 2	250	do	do	25.0	14.0	2.2	2.22
Arco Model No. 3	250	do	do	50.6	15.2	2.4	2.41
Arco Model No. 4	500	do	do	5.5	20.4	2.1	2.57
Arco Model No. 5	500	do	do	12.3	16.0	3.3	2.02
Arco Model No. 6	250	do	Revetment	6.1	11.2	1.8	1.78
Arco Model No. 7	250	do	None	0	10.1	2.5	1.61

*Average crater diameter divided by cube root of charge weight, ft./lbs.$^{1/3}$.

[1] Explosion took place on filled ground over crater from previous test.

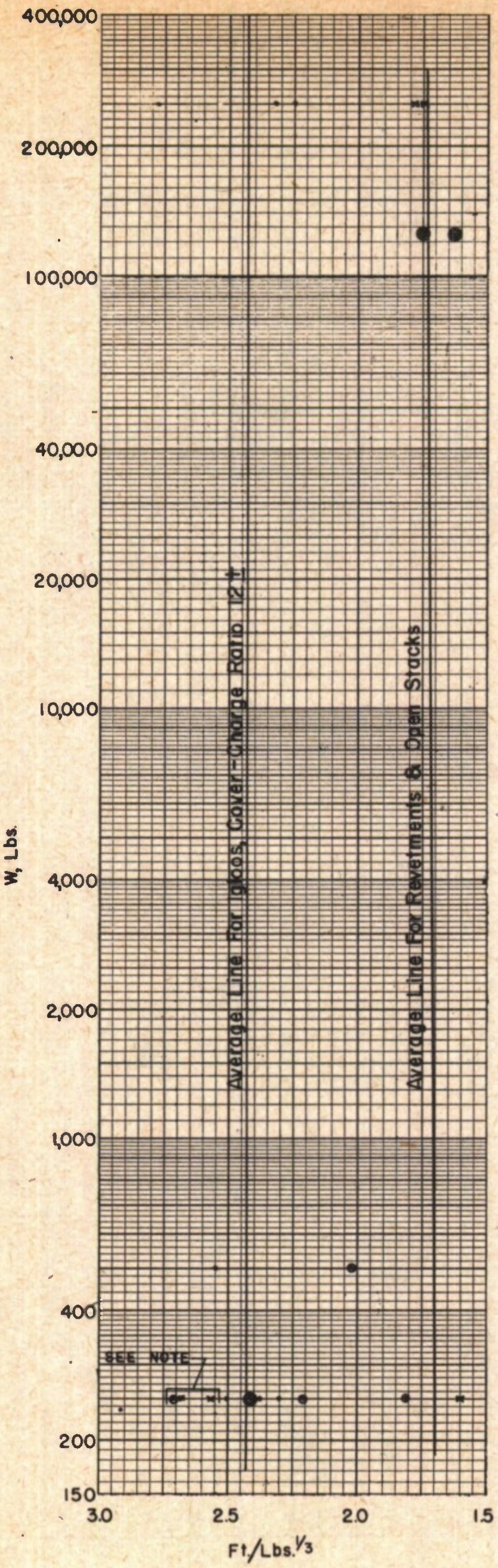
The values of $d/W^{1/3}$ are plotted against charge weight in figure 68. It may be seen from the above table that crater ***diameters*** scale reasonably well for similar explosions, but crater ***depths*** do not, consequently volumes do not. For example, to be true to scale the depth in Arco Model Test No. 1 should be only 1.2 feet (average depth from Arco Nos. 1, 3, and 5), whereas it is actually 2.1 feet or 75 percent greater.

By averaging all the diameters in the foregoing table, exclusive of those of craters in filled ground, the following formulas are obtained, which are more representative of conditions at Arco than the formulas in paragraph 5(A) (2)

$d = 2.37W^{1/3}$ for explosions in igloos, and

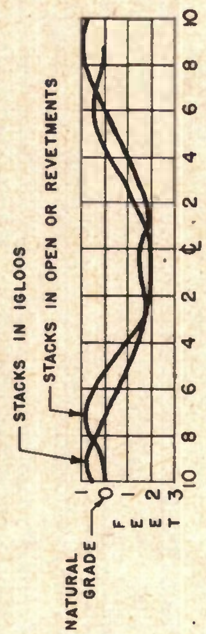
$d = 1.72W^{1/3}$ for explosions of open or revetted stacks,

in which d is apparent crater diameter in feet and W is net charge weight in pounds.



LEGEND

- • Igloo, Cover - Charge Ratio = 12±
- ⊙ " " " " = 25±
- ◎ " " " " = 50±
- × Bare Stack, Cover - Charge Ratio = 0
- ⊗ Revetted Stack, Cover - Charge Ratio = 7±
- ⊗ " " " " " = 15±



TYPICAL CRATER PROFILES

NOTE -

THESE THREE SHOTS ON FILLED GROUND

FIG. 68

Crater Diameter Divided By Cube Root Of Charge Weight Vs Charge Weight, For Arco And Camp Edwards Tests.

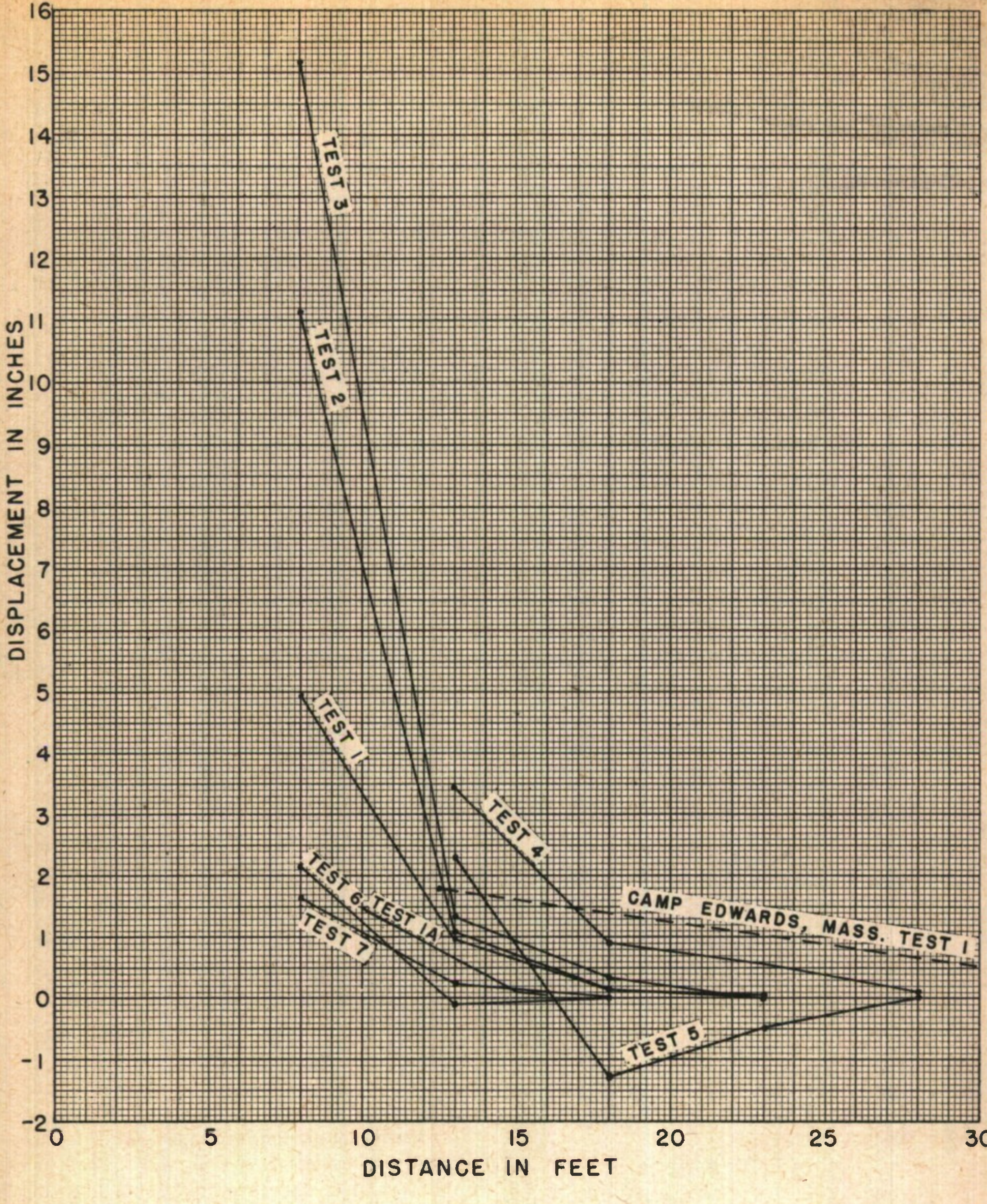


FIG. 69

HORIZONTAL EARTH DISPLACEMENT

Model Igloo Tests

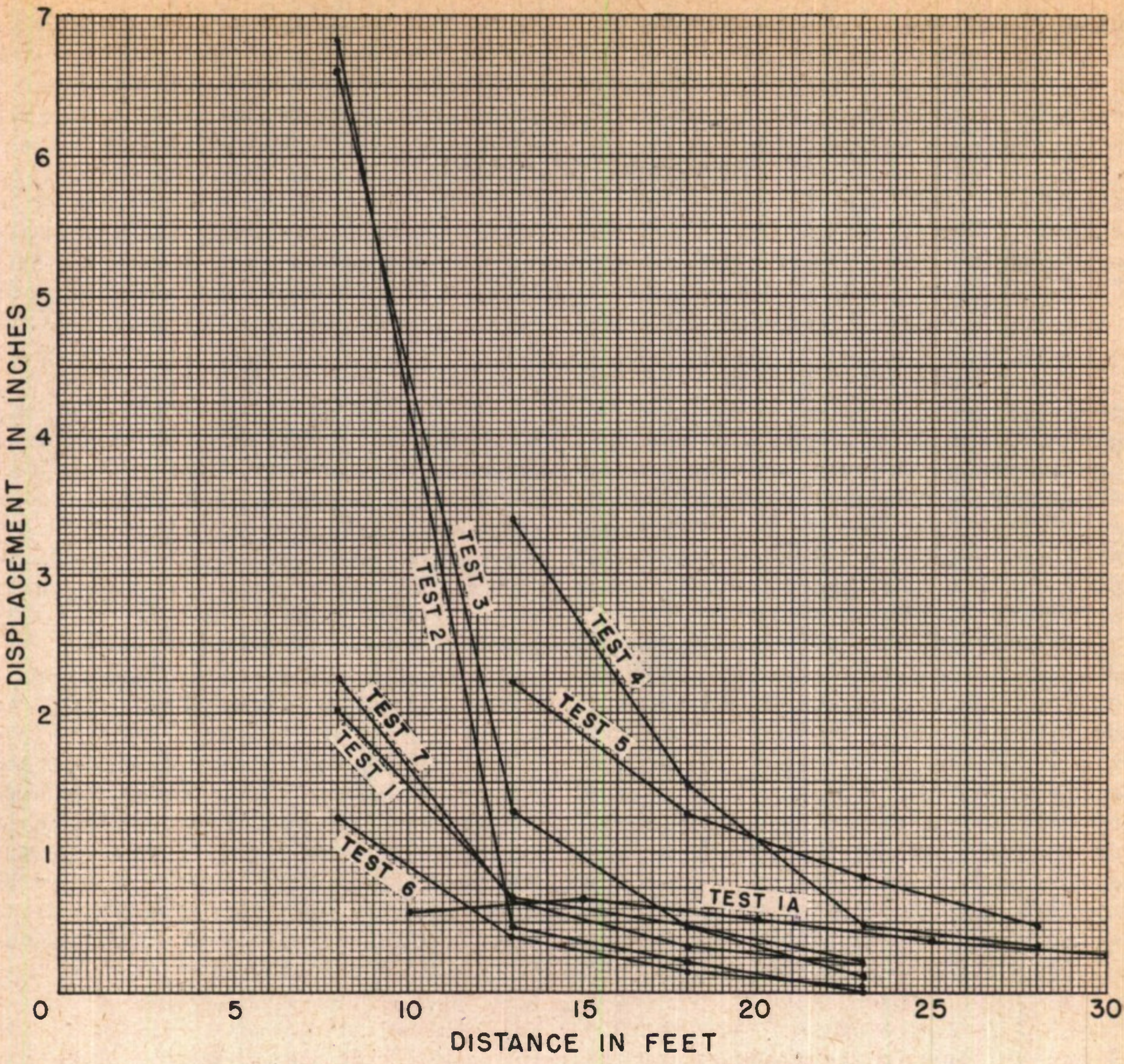


FIG. 70

VERTICAL EARTH DISPLACEMENT

Model Igloo Tests

6. Ground Displacement.

(A) General. Figures 69 and 70 are graphs of permanent horizontal and vertical earth displacement as a function of distance from the center of the crater for each of the model tests. The graphs, which are drawn as straight lines connecting the plotted points, would resemble hyperbolas if drawn as curves, with outward displacements very high close to the crater and decreasing rapidly with distance.

In the 250-pound igloo tests at 8 feet, outward displacements vary from 4.9 to 15.2 inches, while at 13 feet they are only from 0.96 to 1.34 inches. At the latter distance in the 500-pound tests, they were 2.3 and 3.4 inches, and in the revetted and open stack tests, they were −0.1 (inward movement) and +0.25 inches.

The foregoing figures and a comparison of the curves indicate that: (1) horizontal displacement increases markedly at short and medium

distances when charges are placed within igloos, and increases still further when earth cover on the igloos is augmented; (2) horizontal displacements for a given charge weight approach each other and decrease to small values or die out altogether at approximately the same distance, regardless of whether the charge was stored in an igloo with or without increased cover, or in the open; (3) greater charge weights increase both the amplitude and the range of displacement.

(B) Comparison with Camp Edwards Test. To facilitate comparison with the horizontal displacements in the Camp Edwards Test No. 1, a dotted line representing the data reported for that test has also been plotted on the graph. It is seen that the displacement at Camp Edwards was of greater amplitude and extended out much farther than in Arco Model Test 1. Since the charge weights, cover, and other conditions were identical in these two tests, it is clear that the difference was due to the dissimilarity in soils.

It is believed that a consideration of the soils and their relative moisture contents when the tests were held will show that the differences in displacement were to be expected. In the Arco site, the soil is silt, a fine-grained homogeneous material of relatively high imperviousness and compressibility. In the area used for the model tests, the gravel beds lay below the bottoms of the craters and are not believed to have had any appreciable effect on surface displacement. At the time of the tests, as almost always during the summer months, the silt was quite dry and its undisturbed surface contained contraction cracks. As the dryness extended throughout the bed, the entire mass was in a contracted state and probably contained many voids. When the explosion thrust the soil outward, the voids closed up permitting relatively great movement close to the crater, but as the masses were displaced they became consolidated and their resistance increased to a high degree. Beyond a certain distance the discontinuities in the soil prevented further extension of permanent displacement.

The soil at Camp Edwards, on the other hand, was reported to be a sandy clay loam, which, owing to its location in a region of frequent rainfall in all months of the year, presumably contained a high percentage of moisture and was relatively well consolidated. Lacking discontinuities, such material would be expected to displace less at close range but the zone of measurable permanent displacement would be expected to reach out farther.

In Test 5 there was negative or inward permanent displacement at two points. There seems to be no satisfactory explanation for this phenomenon. It may be that the soil in this region acted as an elastic mass which stored up energy during compression and then released it, in part, in the direction of the explosion, causing tension failures permitting the soil to take a permanent set in the reverse direction. It may be that a reflection of the ground shock wave from a discontinuity in the soil, or a combination of reflections, propagated in a reverse direction and exceeded the strain by the primary wave.

The pattern of vertical earth displacements is very similar to that of horizontal displacements. All movements were upward, and the amplitudes are about half as great as the horizontal displacements at close range, but exceed them at distances beyond about 16 feet and extend out considerably farther. The curves are not as consistent but generally follow the same trends (1), (2) and (3) noted above for horizontal displacements.

If these permanent earth displacements or strains in the upper foot of soil can be construed as an indication of the direction and severity of the earth shock which caused them, their main significance is that (1) the target igloo received a much greater blow from ground shock at Camp Edwards than it did at Arco in Test 1 (perhaps six times as great), (2) the direction of the ground shock acting on the target igloo at Arco was almost vertically upward, with a slight outward component, (3) ground shock acting on the target igloo apparently was not appreciably affected by variations in enclosure or earth cover on the charge, (4) ground shock at the range of the target igloo was much more severe (about 5 times as great) when the charge was doubled, (5) surface ground shock appears to vary roughly as the square of the charge weight and inversely as the cube of the distance from the charge, in the dry silt soil at Arco. In better consolidated soils such as the sand-clay mixture at Camp Edwards, and particularly in well graded and compacted sands and gravels the distance exponent would decrease from 3 to perhaps 1½ or less.

(C) Comparison with 1945 Full-Scale Arco Test. Horizontal earth displacements in the 1945 test, wherein an igloo containing 250,000 pounds of high explosives was detonated, averaged about 20 inches outward at 100 feet, 3.5 inches outward at 150 feet and less than 1 inch at 200 feet. These values scale quite well with the average of those

TABLE XXV

DISPLACEMENTS OF TARGET IGLOOS

Test	Transient		Permanent					
	Floor	Floor-arch	Lateral (+, away; −, toward)		Longitudinal		Vertical (+, up; −, down)	
			Front	Rear	Front	Rear	Front	Rear
	Inch	*Inch*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
1	17/32	3/32	......	......	......	......	......	......
1–A	16/32	2/32	−1/4	−3/8	0	0	+0.5	+0.2
2	10/32	3/32	......	......	......	......	......	......
3	12/32	4/32	+1/4	+1/8	0	0	+.2	+.2
4	10/32	10/32	+1 1/8	+3/8	0	0	+.2	+1.1
5	15/32	?5/32	−1	−1 3/4	0	0	−.4	+.7
6	13/32	2/32	0	0	0	0	0	0
7	12/32	2/32	0	0	0	0	0	0
Woods Hole 1	11/32	3/32	......	......	......	......	+1	?+1
Woods Hole 2	13/32	?	+1 1/8	+5/8	?	?	+.6	......

obtained in Tests 1 and 1–A, which were about 2.4 inches at 10 feet, 0.4 inch at 15 feet, and 0.1 inch at 20 feet. Vertical displacements in the full-scale test were not reproduced to scale by the model tests, however, but were considerably greater in the latter case; the full-scale values were about 8 inches upward at 100 feet, 1.2 inches at 150 feet, and about 0.3 inch at 200 feet; the model values were 1 inch at 10 feet, 0.6 inch at 15 feet, and 0.4 inch at 20 feet. At the target igloo distance, the upward ground displacement in the model tests was, relatively speaking, many times that of the full-scale tests.

The failure of the vertical displacements to follow the model law may be due to the lack of a properly scaled force of gravity, which would be expected to affect any vertical movements but not horizontal ones.

The relatively greater upward displacements in the model tests appear to indicate that the vertical component of earth shock was also relatively greater than in the full-scale test.

7. Displacement of Target Igloos.

(A) Transient Movement. The floor gage gives a rough measurement of the floor's maximum upward movement, which has two components: (1) rise of floor slab as a unit and (2) upward flexure at center of slab. If (1) were known it could be subtracted from the floor-gage reading to get net floor deflection due to flexure, and the latter in turn could be subtracted from the arch-floor gage reading to get net arch deflection due to flexure. As it is, neither gage gives a true net reading. Nevertheless, the amplitudes of the readings indicate relative severity of heave due to ground shock (floor gage) and arch strain due to air blast (arch-floor gage).

Consideration of the readings recorded in table XXV leads to the following conclusions:

(1) No consistent trends are developed by the floor gage readings. Those for the 500-pound tests (average 12/32 inch) are even less than those for the 250-pound tests (average 13/32 inch). The presence or absence of an igloo, or augmented earth cover on an igloo enclosing the charge makes little or no difference in the readings. The value of this simple type of gage in tests of this kind therefore seems questionable.

(2) The floor gage readings agree quite well with those obtained in Camp Edwards Tests 1 and 2, which averaged 12/32 inch.

(3) The arch-floor gage registered approximately twice as much average deflection (7/32 inch)

in the 500-pound tests as was registered (3/32 inch) in the 250-pound tests. Actually, air blast was only about 30 percent greater in the 500-pound tests.

(4) Arch-floor deflections in the open and revetted shots were less than in the enclosed shots, which is inconsistent with blast pressures known to have existed. This may mean that floor heave, which is a large part of the arch-floor gage reading, was much less in this case, resulting in a smaller net reading although true arch deflection may have been greater. Such would be the case if ground shock were less in the open and revetted shots.

(5) The arch-floor gage readings in the 250-pound tests, which average 3/32 inch or 0.094 inch, are not far from one-tenth of similar readings obtained in the 1945 250,000-pound test in Igloo B (see reference 3, part VII) which averaged 0.725 inch.

Evidently both of these types of gages, as used in these model tests, were so erratic that important trends were submerged in the scatter of the data.

(B) Permanent Movement. Horizontal and vertical bodily translations of target igloos were measured by surveys.

Comparison of the lateral movements shows that:

(1) Lateral displacements may be either away from or toward the explosion and are of the same order of magnitude in either case. The amplitudes of the displacements are greater than the corresponding horizontal earth displacements given in figure 69, indicating that igloo displacement results from both ground shock and air blast. The air blast apparently increases the movement due to ground shock by about 50 percent. In Test 5, the earth movement and igloo lateral movement were both toward the explosion, the igloo movement being slightly greater. Probably momentum of the igloo causes it to slide and overshoot the amplitude reached by the ground; this is particularly liable to occur with the shallow flatslab type of foundation on which the model igloos are built. In this connection, it should be noted that the foundations of the models closely simulate those of standard Army and Navy igloos with "shallow type" footings.

(2) Lateral displacements in the 500-pound tests averaged four times as great as in the 250-pound series. Increasing the quantity of explosives while maintaining the same distance thus increases displacement approximately as the square of the increase in charge weight. This agrees with the conclusion reached in paragraph 6 in discussing the effect of increased charge weight on surface ground shock.

(3) In the Woods Hole tests, lateral displacements averaged about three times as great as in the Arco model tests. This further confirms the belief that there was greater ground shock at Woods Hole.

The table shows that no longitudinal movement of target igloos occurred. No component of force transverse to the shock front would normally be expected.

The vertical igloo displacements were of the same order of magnitude as the horizontal ones. This is in contrast to the earth displacements in which vertical values generally exceeded horizontal values at the target igloo distance. This indicates that horizontal igloo displacements were greater than those due to ground shock alone and supports the notion that air blast and momentum overshooting on the flat bottom increase lateral movement of the target model igloo. The relative values of vertical displacements also indicate general agreement with the conclusions stated in (2) and (3) above.

The vertical igloo displacements were also fairly close to the vertical earth displacements at the target igloo distance. There seems to be no reason why these values should not be alike.

(C) Comparison of Model Igloo Displacements with Full-Scale Igloo Displacements. (1) Transient: As stated above in 7 (A) (5) the arch-floor gage readings in the 250-pound model tests did not scale exactly but were not far from one-tenth times the values recorded in the 1945 full-scale tests. Those taken in the 500-pound model tests averaged 0.23 inch whereas those recorded in the 500,000-pound full-scale test (detonation of igloo D in 1946 tests) in igloo E averaged 1.04 inches. In this case the scaling is poor, the deflection of the model igloos being relatively over twice as great. In comparing these values it is well to note that the arch reinforcement in the models is patterned after that of the Navy standard igloo and the wartime Army standard igloo, in which there is extrados steel only.[2] The target igloo in

[2] Navy igloo arch reinforcement consists of 4- by 4-inch wire mesh @0.62 lbs./sq. ft., giving 0.14 percent reinforcement at the crown section. Model igloo was reinforced with 4- by 4-mesh of No. 13 gage wire, giving 0.27 percent reinforcement at the crown. Army postwar igloo has 2 layers of ½ inch bars 12 inches o. c., giving 0.27 percent reinforcement in the intrados and a like amount in the extrados.

the 1945 test (igloo B) was of the Navy type, but that of the 1946 test (Igloo E) was of the postwar Army type, having intrados as well as extrados reinforcement, and was consequently better able to resist positive bending moments causing tension in the under surface. In the latter case the blast loading caused only minor and infrequent hairline longitudinal cracking of the inner surface of the arch barrel, whereas in the model tests cracking developed to a greater degree.

(2) Permanent: No data were reported on horizontal permanent displacement of the target igloo in the 1945 full-scale test, but an average downward movement of 0.17 inch at the center of the floor was recorded. This does not compare well with the average rise of 0.35 inch in Arco model test 1–A or the rises of from 1 inch to 0.6 inch reported in the Woods Hole tests. The latter, however, probably included arch deformation, as discussed in reference 4, part VII. In the 1946 Arco test, with a charge weight of 500,000 pounds, no horizontal movement of the target igloo occurred, but there was an average downward movement of 0.71 inch along the floor's centerline. In the 500-pound model tests, the average movement obtained on the centerline at the two ends was 0.61 inch up in Test 4 and ranged from 0.4 inch down to 0.7 inch up in Test 5. These values do not scale well with those of the full-scale test. The question of the degree of permanent displacement of target igloos as a result of blast is highly complicated and includes a large factor of probability. The failure of the acceleration of gravity to scale properly in the model tests and the dissimilarity in foundation construction between the model igloo and the Army prototype (which had footing walls reaching 2 feet 6 inches below grade) would be expected to render agreement in both vertical and horizontal displacements unlikely.

8. Damage to Target Igloos.

(A) Damage in Shots 1 and 1–A Compared with Damage in Camp Edwards Tests. In Shot 1, the minor arch cracking and partial separation of the barrel from the base slab was like in nature, but less in degree, than the damage sustained in Camp Edwards Tests 1 and 2. In Shot 1–A, the front end wall was extensively cracked, but the damage to the rest of the igloo was as slight as in the first test. The extensive cracking of the front wall in this case may be accounted for by the fact that this igloo had been used as target in a previous shot. It appears, then, that the damage suffered at Arco was generally less than at Camp Edwards. Since blast pressures were about the same, the difference is believed to be due to greater ground shock at Camp Edwards. This is in harmony with the discussion of earth displacements and target igloo translation in paragraphs 6 and 7, wherein it was concluded that the ground shock was considerably greater in the Camp Edwards tests. Based on these premises, it is reasoned that the difference in soils of the two sites was responsible for the disparity in damage, particularly in dislocations of the arch barrels from the base slabs in the model tests; and further, was partly responsible for the failure of the Camp Edwards tests to reproduce the damage to the target igloo (B) in the Arco 1945 full-scale test. The failure properly to scale the acceleration of gravity and the differences in foundation construction probably share this responsibility for disagreement.

(B) Comparison with Damage Sustained in Full-Scale Tests. (1) The 250-pound model tests vs. 250,000-pound full-scale tests: Although the cracking of the arch barrels of the model target igloos was minor, it nevertheless somewhat exceeded that experienced in the 1945 full-scale test. The disagreement was small, however, and it seems reasonable to state that the damage to arch barrels scaled approximately. The breaking of the junction between the arch barrel and base slab did not reproduce anything similar in the large test, but this is believed primarily to be due to the difference in foundation construction and the probable weakness of the arch-barrel—floor-slab bond (which is discussed in part I). In addition, earth shock is believed to have been relatively greater in the model tests, as evidenced by greater permanent displacements.

(2) The 500-pound model tests vs. 500,000-pound full-scale tests: The arch barrels of the model target igloos were severely cracked and pieces were broken out in several places. Had the wire mesh reinforcement not been present to hold the segments together, the arch would have collapsed. The floors were similarly broken and loosened from the arch barrels, and the front walls were torn loose from the arch barrels and shattered. In the 1946 full-scale tests with a 500,000-pound charge, the target igloo sustained a number of fine longitudinal and circumferential cracks of the arch barrel, and no cracking of the floor. The rear wall was intact except for one crack, but the front wall suffered severe cracking, its bottom edge was pulled away from the floor slab,

and the peripheral joint between the arch barrel and front wall was ruptured with much spalling of concrete. There is agreement in the character of damage done in both model and full-scale tests, but the degree of damage is considerably greater in the model test. A striking fact is that the failure of the front walls were almost exact parallels except in extent. The most likely causes of these differences in degree of damage are (a) the smaller percentage of reinforcing steel in the concrete of the model igloos, and particularly the lack of tension steel in the intrados of the arch; (b) the questionable bond between the several sections, that is the arch barrel, the floor slab, and the end walls, (c) the differences in foundation construction, (d) the lesser ground shock in the full-scale test, and (e) the failure of gravity to scale.

In general it may be said that the damage done to the target igloos in the full-scale tests was quite similar in character but less serious than in the model tests. Any conclusion regarding igloo spacing or high-explosives capacity based on the results of these or similar model tests therefore would probably be conservative and on the safe side.

(C) Damage in 250-Pound Tests Compared With Damage in 500-pound Tests. The damage done to the target igloo in the 250-pound shots was minor, did not subject the contents to undue hazard, and could have been repaired by grouting the cracks at reasonable expense had the damage occurred in a full-scale igloo. On the contrary, the damage done in the 500-pound shots was major, exposed the contents through loss of the front wall, showered them with fragment of spalled concrete and contributed to their jostling, and could not have been repaired except at considerable pains including construction of a new front wall, and at relatively great expense. The damage done in the 250-pound series may be said to have been acceptable in degree, whereas that inflicted in the 500-pound series may be said to have been unacceptable and igloos should not be spaced so close together that an explosion of one would cause such degree of damage in its neighbors.

(D) Effects of Augmented Earth Cover. Comparison of figures 22, 31, 37, 45 and 52 clearly shows that damage to target igloos is materially reduced when earth cover is increased on primary igloos. For example, when the cover is doubled in Test 2, cracking is diminished and when the cover is quadrupled in Test 3, cracking all but disappears. Had the target igloos also been covered with additional earth, no doubt added protection against air blast would have been given and damage (except that due to ground shock) reduced further or eliminated altogether. If earth cover were increased on all igloos in an actual storage depot, an explosion of a single igloo would be damped more than by standard cover, and adjacent igloos would be protected more than by standard cover. Thus in considering igloo magazines only and not effects on structures outside the storage field, augmented earth cover has a bilateral advantage not disclosed by these tests.

Reduction in damage to a target igloo by virtue of augmented earth cover on an exploding igloo results from energy absorption which attenuates the peak blast pressure and impulse in the air, as discussed in paragraph 2. Reduction in damage by virtue of augmented cover on the target igloo is due to greater cushioning action of the thicker earth layer in reducing the net pressure and impulse exerted on the concrete surface and in increasing resistance to penetration by missiles.

Unfortunately, it takes a relatively large increase in earth cover to effect a small decrease in air blast intensity. It is estimated that a 100 percent increase over standard cover weight absorbs only about an additional 10 percent of the explosion energy. Yet earth displacement is not reduced by augmented earth cover but on the contrary seems greatly amplified at distances materially less than half the standard intra-line igloo spacing. Hence advantages in protection from air blast and missiles would be offset by increased displacement and ground shock if earth cover were augmented in an attempt safely to decrease intra-line spacing to much less than half the standard.

(E) Effect of Revetments. A comparison of figures 57 and 61 fails to reveal any decisive difference between the extent of cracking of the target igloo in the test with a revetment and that of the test without one. This, coupled with the fact that displacements were about the same in both cases, leads to the conclusion that the revetment was of no appreciable benefit in limiting damage to nearby structures.

9. Disturbance of Contents of Target Igloos.

The dummy charges, which consisted of 4-inch channels stacked in pyramidal piles having the same total weights as the primary charges, did not simulate stacks of bombs in full-scale igloos

very well. The channels were relatively much more stable in the stacks than tiers of cylindrical bombs laid on flat wood or steel dunnage in actual magazines. Yet displacement of the channels in the model tests was severe, particularly in the 500-pound series in which the aisle was filled with fallen channels, whereas no movement of the bombs whatsoever could be detected in the 250,000- and 500,000-pound tests (except in one case when the stack was struck by the door which had been blown in, in one of the 1945 tests). Had the bombs in the 500,000-pound test been jostled as severely as the channels in the 500-pound test, all the stacks probably would have collapsed and the storage reduced to a shambles, to say nothing of the increased probability of a detonation. It seems reasonable to conclude that (a) ground shock and target igloo displacement are relatively much more severe in model tests, (b) conclusions based on the results of these or similar model tests in regard to likelihood of derangement of stacks and resultant detonation of high explosives in magazines from the effects of nearby explosions, will be highly conservative and on the safe side.

PART VI. CONCLUSIONS

1. Validity of Model Tests.

These tests have shown that:

a. Apparent crater diameters were independent of the dissimilarity of soils of Camp Edwards and Arco, but the greater moisture content and lack of homogeneity of the Camp Edwards soil caused apparent crater depths to be greater than at Arco. Diameters at both sites scaled well with full-scale explosions but depths and hence volumes did not.. It may be said that diameters follow the model law in coarse to fine-grained homogeneous soils.

b. Permanent displacements of the ground and of the target igloos were much greater at Camp Edwards than at Arco, presumably because the soil at the former site was more compact and in a plastic state. However, vertical earth displacements were also greater in the Arco model tests than in the full scale test, hence it is concluded that the vertical component of displacement is inherently more severe in model tests and does not follow the model law. Horizontal earth displacements seem to follow the model law.

c. Damage to the target igloos was more severe at Camp Edwards and was attributed largely to ground shock. Damage in the Arco model tests seemed to result equally as much from air blast as from earth shock, but was nevertheless somewhat greater than in the full-scale test. The phases of damage due to ground shock do not follow the model law and furthermore depend on the type of soil; accordigly, dnamage to target igloos as a whole cannot be predicted accurately by model tests even where soils are identical. However, the damage is not a great deal more severe in model tests and is quite similar in kind, hence conclusions as to igloo spacing or orientation based on the results of model igloo tests are apt to be somewhat conservative and on the safe side.

d. Summarizing, these tests have shown that model igloo tests are valid in determining:

- Peak air blast pressures.
- Apparent crater diameters.
- Horizontal permanent ground displacement.
- General qualitative behavior of fragments.
- Approximate missile range (in spite of the failure of gravity to scale).
- Transient arch deflection of target igloos.
- Damage to target igloos attributable to air blast.

They are not valid in determining:

- Crater depths and volumes.
- Vertical permanent ground displacements.
- Earth shock (by inference).
- Disturbance of contents of target igloos.
- Damage to target igloos attributable to earth shock.

2. Effect of Increased Earth Cover.

a. On air blast: Thickened earth cover on primary igloos decreases peak air blast pressures generated by detonation of their contents. When 250,000 pounds net weight of TNT are detonated within a standard 27- by 80-foot earth-covered

igloo magazine, the blast pressure at a distance of 4,310 feet (safety distance between inhabited buildings and on unbarricaded storage of 250,000 pounds of high explosives specified by the American Table of Distances) is about 10 percent less than if the same quantity were detonated in the open at that distance. Standard Army and Navy earth-covered igloo magazines do not reduce blast effects sufficiently to warrant dividing the A. T. D. safety distances by two. A chart (fig. 67) indicating to what extent safety distances may be reduced for various amounts of earth cover is given in part V of this report. (This chart is preliminary only and is not recommended for use at this time.)

b. On cratering: Increased cover evidently has no definite effect on crater dimensions, but craters from igloo explosions average about 40 percent greater in apparent diameter than craters from explosions of open or revetted stacks.

c. On earth shock: Increased cover appears to have no appreciable effect on permanent horizontal and vertical displacements of the surface of the ground except at distances within twice the crater radius from the center of the charge. As the edge of the crater is approached, displacements become greatly magnified, are larger when an igloo is present than when the charge was in the open, and increase markedly with augmented earth cover.

d. On damage to target structures: Greater earth cover on an exploded igloo materially lessens damage done to a neighboring igloo. However, igloo intra-line center-to-center spacing cannot be reduced below the crater diameter without entering the region of extreme earth displacements.

3. Value of Revetments.

These tests did not show that any appreciable reduction in air blast or damage to target structures results when a given charge is detonated within a revetment instead of in the open. A slight reduction probably occurs, but the chief value of revetments lies in protecting their contents from face-on blast pressure, low trajectory missiles, and heat from external explosions.

PART VII. REFERENCES

1. TEST PROGRAM—1946—Explosives Safety Tests of Igloos and Inhabited Buildings; by Col. D. C. Hall, Ord. Dept., USA approved in meeting No. 88 of the Army-Navy Explosives Safety Board; 19 February 1946.
2. Memorandum for the Army-Navy Explosives Safety Board, Subject: Extra Cover for Igloos, from Capt. E. R. Gayler, CEC, USN (Ret.), dated 19 February 1946.
3. Igloo Tests, Arco, Idaho, 1945; Army-Navy Explosives Safety Board Technical Paper No. 3, June 1, 1946.
4. Test on Scale-Model Igloo-Type Storage Magazines, by W. D. Kennedy and W. E. Curtis, Underwater Explosives Research Laboratory, Woods Hole Oceanographic Institution, Woods Hole, Mass., submitted by P. M. Fye, Research Director, August 1, 1946.
5. Construction and Characteristics of Model Ammunition Storage Magazines; NDRC Report No. A–353; by N. M. Newmark, C. P. Atkins, and E. E. Bauer, University of Illinois, November 19, 1945.
6. Igloo Magazine Test Program, 1946, Naval Proving Ground, Arco, Idaho; enclosure to Memorandum for Army-Navy Explosives Safety Board from Comdr. R. L. Mann, CEC, USN, dated 9 July 1946.
7. Memorandum for file, subject: Theory of Crusher Gages; Navy Department, Bureau of Ordnance, file A16 (D. N. D.) (Re6b), from G. K. Hartmann, dated 25 September 1942 (Confidential).
8. The Calibration of Aberdeen Paper Blast Meters assembled with "Rap-in-Wax" waxed paper and of Tinfoil Indentation Blast Gages; Ballistic Research Laboratories, Aberdeen Proving Ground, Memorandum Report No. 430, by S. Lasher and J. N. Sarmousakis, 22 May 1946.
9. Weapon Data—Fire, Impact, Explosion; by the Princeton University Station, OSRD 6053, September 1945.
10. Explosions, Their Antomy and Destructiveness, by C. S. Robinson, April 1944.

APPENDIX A. FIELD DATA

ABERDEEN PAPER BLAST METER RECORDS

TEST NO. 1. DATE: 30 JULY 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
30	......	......	......	9	......	12
38	9	......	9	......	9	......
50	8	......	8	9	9	8
64	7	......	7	......	8	......
82	7	7	7	......	7	......
106	6	......	6	6	7	6
135	6	......	5	......	7	......
173	4	......	3	......	6	......
222	3	4	3	3	4	3
285	2	......	2	......	2	......
365	1	1	0	1	1	0
469	0	......	0	......	0	......

TEST NO. 1A. DATE: 10 AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
30	9	......	......	......	10	......
106	6	......	......	......	7	......
285	2	......	......	......	2	......

TEST NO. 2. DATE: 1 AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
30	......	......	......	9	......	9
38	9	......	9	......	8	......
50	8	......	7	9	9	8
64	8	......	7	......	7	......
82	7	8	6	......	7	......
106	5	......	5	6	5	6
135	5	......	5	......	4	......
173	4	......	4	......	3	......
222	3	4	3	3	4	3
285	2	......	2	......	2	......
365	1	0	0	0	0	0
469	0	......	0	......	0	......

TEST NO. 3. DATE: 2 AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
30	......	......	......	9	......	9
38	9	......	7	......	8	......
50	8	......	7	7	7	7
64	7	......	7	......	6	......
82	6	6	7	......	5	......
106	6	......	5	5	4	6
135	5	......	4	......	3	......
173	4	......	3	......	4	......
222	3	0	3	3	2	3
285	1	......	0	......	0	......
365	0	0	0	0	0	0
469	0	......	0	......	0	......

ABERDEEN PAPER BLAST METER RECORDS
(continued)

TEST NO. 4. DATE: AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
50	10	9	9	...	...	...
64	10	9	9	...	...	...
82	9	9	7	...	...	...
106	7	8	6	...	...	...
135	4	7	6	...	...	...
173	4	6	4	...	...	...
222	3	5	3	...	...	...
285	4	5	3	...	...	...
365	2	2	0	...	...	...
469	1	1	0	...	...	...
600	0	0	0	...	...	...

TEST NO. 5. DATE: AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
50	10	9	9	...	...	...
64	9	9	8	...	...	...
82	8	8	7	...	...	...
106	7	7	4	...	...	...
135	5	6	4	...	...	...
173	5	5	3	...	...	...
222	2	4	3	...	...	...
285	2	3	2	...	...	...
365	2	3	0	...	...	...
469	0	0	0	...	...	...
600	0	0	0	...	...	...

TEST NO. 6. DATE: AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
38	9	...	9	...	9	...
50	9	...	9	...	9	...
64	7	...	8	...	9	...
82	7	...	8	...	8	...
106	7	...	7	...	5	...
135	...	...	...	...	...	...
173	6	...	7	...	5	...
222	5	...	4	...	3	...
285	3	...	2	...	2	...

TEST NO. 7. DATE: AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
38	9	...	8	...	10	...
50	9	...	8	...	9	...
64	8	...	7	...	8	...
82	7	...	7	...	8	...
106	7	...	7	...	7	...
135	...	...	...	...	...	...
173	4	...	5	...	5	...
222	3	...	4	...	4	...
285	3	...	3	...	3	...

ALUMINUM FOIL BLAST METER RECORDS

TEST NO. 1. DATE: 30 JULY 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
30.....	8	10	5	7	11	10
38.....	6	......	5	......	7	......
50.....	4	......	3	4	4	4
64.....	2	......	2	......	4	......
82.....	1	1	1	......	2	......
106....	0	......	0	1	1	0
135....	0	......	0	......	0	......
173....	0	......	0	......	0	......
222....	0	0	0	0	0	0

TEST NO. 2. DATE: 1 AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
30.....	9	......	4	......	6	6
38.....	6	......	3	......	5	......
50.....	3	......	2	......	3	3
64.....	2	......	2	......	2	......
82.....	1	......	0	......	1	......
106....	0	......	......	......	0	......

TEST NO. 3. DATE: 2 AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
30.....	7	......	1	......	5	5
38.....	4	......	2	......	3	......
50.....	3	......	2	......	1	2
64.....	2	......	0	......	1	......
82.....	0	......	0	......	1	......
106....	0	......	......	......	0	......

TEST NO. 4. DATE: AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
38.....	11	10	6	......	......	......
50.....	9	8	5	......	......	......
64.....	7	5	3	......	......	......
82.....	3	3	2	......	......	......
106....	4	2	0	......	......	......
135....	1	1	0	......	......	......
173....	0	0	......	......	......	......

ALUMINUM FOIL BLAST METER RECORDS
(continued)

TEST NO. 5. DATE: AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
38	12	7	5	......	......	......
50	9	5	4	......	......	......
64	6	4	2	......	......	......
82	4	2	1	......	......	......
106	2	1	0	......	......	......
135	2	0	0	......	......	......
173	0	0	......	......	......	......

TEST NO. 6. DATE: AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
38	6	......	7	......	7	......
50	4	......	6	......	6	......
64	3	......	4	......	4	......
82	2	......	3	......	1	......

TEST NO. 7. DATE: AUGUST 1946

Distance (feet)	Number of smallest diaphragm ruptured					
	Meter line No. 1	Meter line No. 2	Meter line No. 3	Meter line No. 4	Meter line No. 5	Meter line No. 6
38	7	......	4	......	11	......
50	5	......	2	......	6	......
64	3	......	1	......	4	......
82	2	......	1	......	2	......

BALL CRUSHER GAGE RECORD

TEST 1. 30 July 1946

Meter line	Distance from charge (feet)	Gage No.	Initial diameter (in. X 10^4)	Final diameter (in. X 10^4)	Deformation (in. X 10^6)
1	12	267	1,554	1,554	0
1	12	75	1,553	1,555	0
1	15	298	1,553	1,553	0
1	15	318	1,554	1,554	0
2	10	287	1,553	1,553	0
2	10	110	1,555	1,557	0
2	10	300	1,558	1,558	0
2	12	299	1,554	1,555	0
2	12	288	1,553	1,552	100
2	18	311	1,553	1,554	0
2	18	068	1,553	1,553	0
3	12	290	1,554	1,555	0
3	12	314	1,555	1,555	0
3	15	291	1,554	1,555	0
3	15	295	1,554	1,555	0
4	12	72	1,555	1,555	0
4	12	98	1,554	1,551	300
5	12	305	1,554	1,553	100
5	12	68	1,555	1,556	0
5	15	108	1,554	1,554	0
5	15	04	1,554	1,554	0
6	12	65	1,553	1,554	0
6	12	316	1,554	1,556	0

TEST 1-A. 10 August 1946

Meter line	Distance from charge (feet)	Gage No.	Initial diameter (in. X 10^4)	Final diameter (in. X 10^4)	Deformation (in. X 10^6)
1	10	287	1,556	1,553	300
5	8	108	1,554	1,554	0
5	10	298	1,554	1,554	0
5	12	299	1,554	1,556	0
5	12	Arco-0	1,554	1,490	6,400

BALL CRUSHER GAGE RECORD
(continued)

TEST 2. 1 August 1946

Meter line	Distance fram charge (feet)	Gage Na.	Initial diameter (in. X 10⁴)	Final diameter (in. X 10⁴)	Defarmatian (in. X 10⁶)
1	7	267	1,556	1,556	0
1	12	75	1,556	1,532	2,400
1	15	298	1,554	1,553	100
1	15	318	1,558	1,537	2,100
2	7	287	1,555	1,555	0
2	10	266	1,554	1,552	200
2	10	300	1,554	1,536	1,800
2	12	299	1,556	1,554	200
2	12	288	1,553	1,552	100
2	18	311	1,553	1,551	200
2	18	065	1,555	1,553	200
3	12	290	1,556	1,519	3,700
3	7	314	1,554	1,536	1,800
3	15	291	1,554	1,543	1,100
3	15	295	1,554	1,553	100
4	12	72	1,554	1,554	0
4	12	98	1,555	1,492	6,300
5	7	305	1,556	1,512	4,400
5	12	68	1,554	1,554	0
5	15	108	1,556	1,555	100
5	15	04	1,556	1,554	200
6	12	65	1,555	1,551	400
6	12	316	1,554	1,541	1,300

TEST 3—Na readings taken.

TEST 4. 5 August 1946

Meter line	Distance fram charge (feet)	Gage Na.	Initial diameter (in. X 10⁴)	Final diameter (in. X 10⁴)	Defarmatian (in. X 10⁶)
1	10	288	1,553	1,451	10,200
1	12	72	1,555	1,512	4,300
1	16	316	1,554	1,534	2,000
2	10	291	1,554	1,532	2,200
2	12	290	1,554	1,541	1,300
2	16	287	1,555	1,538	1,700
3	10	305	1,553	1,535	1,800
3	12	298	1,554	1,539	1,500
3	16	04	1,555	1,538	1,700
4	10	065	1,554	1,530	2,400
4	12	98	1,554	1,536	1,800
4	16	295	1,554	1,550	400

TEST 5. 5 AUGUST 1946

Meter line	Distance fram charge (feet)	Gage Na.	Initial diameter (in. X 10⁴)	Final diameter (in. X 10⁴)	Defarmatian (in. X 10⁶)
1	10	304	1,554	1,453	10,100
1	12	101	1,554	1,455	9,900
1	16	266	1,554	1,487	6,700
2	10	299	1,554	1,541	1,300
2	12	75	1,554	1,527	2,700
2	16	65	1,555	1,543	1,200
3	10	267	1,554	1,539	1,500
3	12	68	1,555	1,546	900
3	16	314	1,553	1,544	900
4	10	300	1,553	1,533	2,000
4	12	311	1,554	1,553	100
4	16	318	1,553	1,553	0

BALL CRUSHER GAGE RECORD
(continued)

TEST 6. 8 AUGUST 1946

Meter line	Distance from charge (feet)	Gage No.	Initial diameter (in. X 10⁴)	Final diameter (in. X 10⁴)	Deformation (in. X 10⁶)
1	7	267	1,554	1,513	4,100
1	10	98	1,554	1,535	1,900
1	12	305	1,554	1,539	1,500
2	7	300	1,554	1,503	5,100
2	10	266	1,554	1,501	5,300
2	12	04	1,554	1,532	2,200
3	7	299	1,554	1,527	2,700
3	10	316	1,554	1,541	1,300
3	12	68	1,554	1,531	2,300
5	7	108	1,554	1,530	2,400
5	10	298	1,554	1,542	1,200
5	12	72	1,554	1,534	2,000
5	12	Arco–0	1,554	1,444	11,000

TEST 7. 8 AUGUST 1946

Meter line	Distance from charge (feet)	Gage No.	Initial diameter (in. X 10⁴)	Final diameter (in. X 10⁴)	Deformation (in. X 10⁶)
1	7	065	1,554	1,509	4,500
1	10	291	1,555	1,524	3,100
1	12	97	1,554	1,526	2,800
2	7	314	1,554	1,523	3,100
2	10	290	1,555	1,529	2,600
2	12	287	1,555	1,528	2,700
3	7	101	1,554	1,529	2,500
3	10	311	1,554	1,503	5,100
3	12	318	1,553	1,529	2,400
5	7	288	1,554	1,527	2,700
5	10	295	1,553	1,494	5,900
5	12	75	1,553	1,532	2,100
5	12	Arco–0	1,555	1,432	12,300

EARTH DISPLACEMENT NOTES

MODEL IGLOO TEST NO. 1

	Original elevation	Remeasured elevation	Difference	Original distance	Remeasured distance	Difference
N						
8′	100.96	Blown out	....	8′–0″	Blown out	....
13′	100.83	100.86	+0.03′	13′–0″	13′–0½″	+½″
18′	100.76	100.79	+.03′	18′–0″	18′–0¼″	+¼″
23′	100.68	100.70	+.02′	23′–0″	23′–0″	....
NW						
8′	100.88	101.00	+.12′	8′–0″	8′–4¼″	+4¼″
13′	100.96	101.02	+.06′	13′–0″	13′–0½″	+½″
18′	100.76	100.80	+.04′	18′–0″	18′–0¼″	+¼″
23′	100.71	100.73	+.02′	23′–0″	23′–0″	....
W						
8′	100.91	101.27	+.36′	8′–0″	8′–5″	+05″
13′	100.79	100.88	+.09′	13′–0″	13′–2″	+2″
18′	100.83	100.87	+.04′	18′–0″	18′–1″	+1″
23′	100.82	100.85	+.03′	23′–0″	23′–0¼″	+¼″

MODEL IGLOO TEST 1 (continued)

	Original elevation	Remeasured elevation	Difference	Original distance	Remeasured distance	Difference
SW						
8'............	101.01	100.12	+.11'	8'–0"	8'–3"	+3"
13'............	100.95	101.02	+.07'	13'–0"	13'–2"	+2"
18'............	101.34	101.38	+.04'	18'–0"	18'–0½"	+½"
23'............	101.33	101.34	+.01'	23'–0"	23'–0"	....
S						
8'............	100.95	101.09	+.14'	8'–0"	8'–7"	+7"
13'............	101.05	101.07	+.02'	13'–0"	13'–0⅝"	+⅝"
18'............	100.95	100.98	+.03'	18'–0"	18'–0½"	+½"
23'............	101.05	101.07	+.02'	23'–0"	23'–0¼"	+¼"
SE						
8'............	100.95	101.06	+.11'	8'–0"	8'–3¼"	+3¼"
13'............	100.90	100.94	+.04'	13'–0"	13'–0¾"	+¾"
18'............	100.91	100.95	+.04'	18'–0"	18'–0½"	+½"
23'............	100.98	100.99	+.01'	23'–0"	23'–0¼"	+¼"
E						
8'............	100.91	101.07	+.16'	8'–0"	8'–8"	+8"
13'............	100.98	101.06	+.08'	13'–0"	13'–1½"	+1½"
18'............	101.06	101.12	+.06'	18'–0"	17'–10"	−2"
24'............	101.18	101.20	+.02'	24'–0"	24'–0"	....
NE						
8'............	100.93	101.11	+.18'	8'–0"	8'–4"	+4"
13'............	100.88	100.95	+.07'	13'–0"	13'–0"	....
18'............	100.88	100.92	+.04'	18'–0"	18'–0"	....
23'............	100.91	100.93	+.02'	23'–0"	23'–0"	....

MODEL IGLOO TEST NO. 1-A

	Original elevation	Remeasured elevation	Difference	Original distance	Remeasured distance	Difference
NE						
10'..........	100.05	100.09	+0.04'	10'–0"	10'–1½"	+1½"
15'..........	100.07	100.12	+.05'	15'–0"	15'–0"	....
20'..........	100.06	100.10	+.04'	20'–0"	20'–0"	....
25'..........	100.05	100.08	+.03'	25'–0"	25'–0"	....
30'..........	99.98	99.99	+.01'	30'–0"	30'–0"	....

MODEL IGLOO TEST 1-A (continued)

	Original elevation	Remeasured elevation	Difference	Original distance	Remeasured distance	Difference
NW						
10'..........	100.11	100.14	+.03'	10'-0"	10'-1½"	+1½"
15'..........	100.14	100.19	+.05'	15'-0"	15'-0¼"	+¼"
20'..........	100.14	100.17	+.03'	20'-0"	20'-0"	....
25'..........	100.11	100.14	+.03'	25'-0"	25'-0"	....
30'..........	100.16	100.18	+.02'	30'-0"	30'-0"	....
SW						
10'..........	100.22	100.29	+.07'	10'-0"	10'-1¾"	+1¾"
15'..........	100.20	100.25	+.05'	15'-0"	15'-0¼"	+¼"
20'..........	100.37	100.42	+.05'	20'-0"	20'-0"	....
25'..........	100.41	100.44	+.03'	25'-0"	25'-0"	....
30'..........	100.31	100.34	+.03'	30'-0"	30'-0"	....
SE						
10'..........	100.20	100.25	+.05'	10'-0"	10'-1⅜"	+1⅜"
15'..........	100.14	100.21	+.07'	15'-0"	15'-0"	....
20'..........	100.11	100.16	+.05'	20'-0"	20'-0"	....
25'..........	100.12	100.15	+.03'	25'-0"	25'-0"	....
30'..........	100.00	100.03	+.03'	30'-0"	30'-0"	....

MODEL IGLOO TEST NO. 2

	Original elevation	Remeasured elevation	Difference	Original distance	Remeasured distance	Difference
N						
8'..........	101.07	Blown out	....	8'-0"	....	....
13'..........	101.01	101.03	+.02'	13'-0"	13'-0"	....
18'..........	100.86	100.88	+.02'	18'-0"	18'-0½"	+½"
23'..........	100.80	100.80	.0	23'-0"	23'-0"	....
NW						
8'..........	100.78	101.30	+.52'	8'-0"	8'-6½"	+6½"
13'..........	100.73	100.77	+.04'	13'-0"	13'-0"	....
18'..........	101.00	101.03	+.03'	18'-0"	17'-10"	−2"
23'..........	100.54	100.54	.0	23'-0"	23'-0"	....
W						
8'..........	100.77	101.36	+.59'	8'-0"	8'-11½"	+11½"
13'..........	100.95	100.97	+.02'	13'-0"	13'-½"	+½"
18'..........	100.61	100.62	+.01'	18'-0"	18'-0"	....
23'..........	100.56	100.56	.0	23'-0"	23'-0"	....

MODEL IGLOO TEST NO. 2—(Continued)

	Original elevation	Remeasured elevation	Difference	Original distance	Remeasured distance	Difference
SW						
8′..........	100.78	101.01	+.23′	8′–0″	8′–6″	+6″
13′..........	100.86	100.89	+.03′	13′–0″	13′–1¼″	+1¼″
18′..........	101.10	101.12	+.02′	18′–0″	17′–11¾″	−¼″
23′..........	100.79	100.79	.0	23′–0″	23′–0″	....
S						
8′..........	101.01	101.67	+.66′	8′–0″	8′–11″	+11″
13′..........	101.05	101.08	+.03′	13′–0″	13′–1½″	+1½″
18′..........	101.01	101.02	+.01′	18′–0″	18′–0⅜″	+⅜″
23′..........	100.96	100.96	.0	23′–0″	23′–0″	....
SE						
8′..........	101.08	101.38	+.30′	8′–0″	8′–7¾″	+7¾″
13′..........	100.94	101.01	+.07′	13′–0″	13′–1½″	+1½″
18′..........	101.18	101.19	+.01′	18′–0″	18′–0¾″	+¾″
23′..........	101.24	101.24	.0	23′–0″	23′–0″	....
E						
8′..........	100.92	101.46	+.54′	8′–0″	9′–3¼″	+1′–3¼″
13′..........	101.07	101.12	+.05′	13′–0″	13′–2″	+2″
18′..........	101.07	101.09	+.02′	18′–0″	18′–0½″	+½″
24′..........	101.26	101.26	.0	24′–0″	24′–0″	....
NE						
8′..........	100.98	102.12	+1.14′	8′–0″	9′–8¼″	+1′–8¼″
13′..........	101.10	101.15	+.05′	13′–0″	13′–2″	+2″
18′..........	100.92	101.94	+.02′	18′–0″	18′–0¼″	+¼″
23′..........	101.08	101.08	.0	23′–0″	23′–0″	....

MODEL IGLOO TEST NO. 3

	Original elevation	Remeasured elevation	Difference	Original distance	Remeasured distance	Difference
N						
8′..........	100.40	Blown out	....	8′–0″	....	....
13′..........	100.25	100.39	+0.14′	13′–0″	13′–0⅛″	+⅛″
18′..........	100.30	100.36	+.06′	18′–0″	17′–11¾″	−¼″
23′..........	100.31	100.32	+.01′	23′–0″	23′–0″	....

	Original elevation	Remeasured elevation	Difference	Origininal distance	Remeasured distance	Difference
NW						
8'..........	100.43	Blown out	....	8'-0"	....	....
13'..........	100.53	100.71	+.18'	13'-0"	13'- 1½"	+1½"
18'..........	100.40	100.47	+.07'	18'-0"	17'-11⅝"	−⅜"
23'..........	100.29	100.30	+.01'	23'-0"	23'-0"	....
W						
8'..........	100.46	Blown out	....	8'-0"	....	....
13'..........	100.50	100.63	+.13'	13'-0"	13'- 3⅛"	+3⅛"
18'..........	100.52	100.58	+.06'	18'-0"	18'- 0⅜"	+⅜"
23'..........	100.48	100.50	+.02'	23'-0"	23'- 0"	....
SW						
8'..........	100.38	100.89	+.51'	8'-0"	8'- 9¾"	+9¾"
13'..........	100.48	100.53	+.05'	13'-0"	13'- 0½"	+½"
18'..........	100.64	100.68	+.04'	18'-0"	18'- 0"	....
23'..........	100.51	100.51	.0	23'-0"	23'- 0"	....
S						
8'..........	100.44	100.65	+.21'	8'-0"	8'-11"	+11"
13'..........	100.45	100.50	+.05'	13'-0"	13'- 0¼"	+¼"
18'..........	100.57	100.60	+.03'	18'-0"	18'- 0"	....
23'..........	100.49	100.50	+.01'	23'-0"	23'- 0"	....
SE						
8'..........	100.51	101.11	+.60'	8'-0"	9'- 2½"	+1'- 2½"
13'..........	100.44	100.54	+.10'	13'-0"	13'- 1½"	+1½"
18'..........	100.42	100.46	+.04'	18'-0"	18'- 0"	....
23'..........	100.59	100.60	+.01'	23'-0"	23'- 0"	....
E						
8'..........	100.43	Out	....	8'-0"	Out	....
13'..........	100.45	100.59	+.14'	13'-0"	13'- 1⅞"	+1⅞"
18'..........	100.51	100.55	+.04'	18'-0"	18'- 0¼"	+¼"
24'..........	100.60	100.62	+.02'	24'-0"	24'- 0"	....
NE						
8'..........	100.44	101.33	+.89'	8'-0"	10'- 1½"	+2'- 1¼"
13'..........	100.48	100.60	+.12'	13'-0"	13'-1¾"	+1¾"
18'..........	100.45	100.50	+.05'	18'-0"	18'- 0¼"	+¼"
23'..........	100.33	100.35	+.02'	23'-0"	23'- 0"	....

	Original elevation	Remeasured elevation	Difference	Original distance	Remeasured distance	Difference
N						
8′	100.31	Out	....	8′–0″	....	....
13′	100.42	100.77	+0.35′	13′–0″	13′–2½″	+2½″
18′	100.38	100.46	+.08′	18′–0″	18′–0½″	+½″
23′	100.41	100.47	+.06′	23′–0″	23′–0¼″	+¼″
28′	100.42	100.45	+.03′	28′–0″	28′–0¼″	+¼″
NW						
8′	100.48	Out	....	8′–0″	....	....
13′	100.43	100.78	+.35′	13′–0″	13′–5″	+5″
18′	100.48	100.59	+.11′	18′–0″	18′–0⅜″	+⅜″
23′	100.39	100.44	+.05′	23′–0″	23′–1″	+1″
28′	100.40	100.43	+.03′	28′–0″	28′–0½″	+½″
W						
8′	100.48	Out	....	8′–0″	....	....
13′	100.41	100.66	+.25′	13′–0″	13′–3¼″	+3¼″
18′	100.50	100.67	+.17′	18′–0″	18′–0½″	+½″
24′	100.70	100.75	+.05′	24′–0″	24′–0¾″	+¾″
29′	100.43	100.45	+.02′	29′–0″	29′–0″	....
SW						
8′	100.35	Out	....	8′–0″	....	....
13′	100.42	100.62	+.20′	13′–0″	13′–3½″	+3½″
18′	100.54	100.62	+.08′	18′–0″	18′–1½″	+1½″
23′	100.44	100.50	+.06′	23′–0″	23′–1″	+1″
28′	100.40	100.44	+.04′	28′–0″	28′–0¼″	+¼″
S						
8′	100.38	Out	....	8′–0″	....	....
13′	100.66	100.89	+.23′	13′–0″	13′–2″	+2″
18′	100.45	100.52	+.07′	18′–0″	18′–0¾″	+¾″
23′	100.47	100.50	+.03′	23′–0″	23′–0½″	+½″
28′	100.36	100.41	+.05′	28′–0″	28′–0⅜″	+⅜″
SE						
8′	100.38	Out	....	8′–0″	....	....
13′	100.47	100.71	+.24′	13′–0″	13′–2½″	+2½″
18′	100.50	100.57	+.07′	18′–0″	18′–0½″	+½″
23′	100.46	100.50	+.04′	23′–0″	23′–0⅜″	+⅜″
28′	100.51	100.48	−.03′	28′–0″	27′–11½″	−½″
E						
8′	100.37	Out	....	8′–0″	....	....
13′	100.44	100.75	+.31′	13′–0″	13′–4¼″	+4¼″
18′	100.45	100.48	+.03′	18′–0″	18′–1½″	+1½″
23′	100.48	100.49	+.01′	23′–0″	23′–0½″	+½″
28′	100.48	100.49	+.01′	28′–0″	28′–0″	....
NE						
8′	100.32	Out	....	8′–0″	....	....
13′	100.37	100.71	+.34′	13′–0″	13′–4½″	+4½″
18′	100.42	100.51	+.09′	18′–0″	18′–1½″	+1½″
23′	100.42	100.43	+.01′	23′–0″	23′–0⅜″	+⅜″
28′	100.44	100.45	+.01′	28′–0″	28′–0¼″	+¼″

MODEL IGLOO TEST NO. 5

	Original elevation	Remeasured elevation	Difference	Original distance	Remeasured distance	Difference
N						
8′	100.38	Out	...	8′–0″	...	...
13′	100.41	100.87	+0.46′	13′–0″	13′– 5½″	+5½″
18′	100.44	100.57	+.13′	18′–0″	17′–10″	−2″
23′	100.27	100.37	+.10′	23′–0″	22′–11″	−1″
28′	100.21	100.27	+.06′	28′–0″	28′– 0″	...
NW						
8′	100.59	Out	...	8′–0″	...	...
13′	100.55	100.67	+.12′	13′–0″	13′– 2¼″	+2¼″
18′	100.56	100.64	+.08′	18′–0″	17′–10″	−2″
23′	100.53	100.60	+.07′	23′–0″	22′–10¾″	−1¼″
28′	100.50	100.54	+.04′	28′–0″	28′– 0″	...
W						
8′	100.57	Out	...	8′–0″	...	...
13′	100.65	100.78	+.13′	13′–0″	13′– 1¾″	+1¾″
18′	100.64	100.84	+.20′	18′–0″	17′– 8½″	−3½″
24′	100.93	100.98	+.05′	24′–0″	24′– 0⅜″	+ ⅜″
29′	100.86	100.86	.0	29′–0″	29′– 0″	...
SW						
8′	100.40	Out	...	8′–0″	...	...
13′	100.57	100.70	+.13′	13′–0″	13′– 0¾″	+ ¾″
18′	100.71	100.80	+.09′	18′–0″	17′–11″	−1″
23′	100.66	100.73	+.07′	23′–0″	22′–10½″	−1½″
28′	100.68	100.71	+.03′	28′–0″	28′– 0″	...
S						
8′	100.42	Out	...	8′–0″	...	...
13′	100.45	100.51	+.06′	13′–0″	13′– 2″	+2″
18′	100.52	100.61	+.09′	18′–0″	17′–11″	−1″
23′	100.49	100.55	+.06′	23′–0″	23′– 0″	...
28′	100.50	100.54	+.04′	28′–0″	28′– 0″	...
SE						
8′	100.49	Out	...	8′–0″	...	...
13′	100.48	100.63	+.15′	13′–0″	13′– 2¼″	+2¼″
18′	100.53	100.62	+.09′	18′–0″	18′– 1¼″	+1¼″
23′	100.52	100.59	+.07′	23′–0″	23′– 0″	...
28′	100.40	100.44	+.04′	28′–0″	28′– 0″	...
E						
8′	100.42	Out	...	8′–0″	...	...
13′	100.47	100.77	+.30′	13′–0″	13′– 2½″	+2½″
18′	100.46	100.55	+.09′	18′–0″	17′–11″	−1″
23′	100.40	100.46	+.06′	23′–0″	23′– 0″	...
28′	100.31	100.36	+.05′	28′–0″	28′– 0″	...
NE						
8′	100.34	Out	...	8′–0″	...	...
13′	100.33	100.47	+.14′	13′–0″	13′– 1½″	+1½″
18′	100.35	100.43	+.08′	18′–0″	17′– 11″	−1″
23′	100.32	100.40	+.08′	23′–0″	22′–11½″	− ½″
28′	100.35	100.41	+.06′	28′–0″	28′– 0″	...

	Original elevation	Remeasured elevation	Difference	Original distance	Remeasured distance	Difference
N						
8′...........	100.40	100.44	+0.04′	8′–0″	8′– 2″	+2″
13′..........	100.50	100.55	+.05′	13′–0″	12′–11¾″	– ¼″
18′..........	100.39	100.39	.0	18′–0″	18′– 0″	....
23′..........	100.34	100.36	+.02′	23′–0″	23′– 0″	....
NW						
8′...........	100.34	100.44	+.10′	8′–0″	8′– 2½″	+2½″
13′..........	100.29	100.30	+.01′	13′–0″	13′– 0″	....
18′..........	100.43	100.46	+.03′	18′–0″	18′– 0″	....
23′..........	100.34	100.36	+.02′	23′–0″	23′– 0″	....
8′...........	100.40	100.60	+.20′	8′–0″	8′– 4″	+4″
13′..........	100.41	100.46	+.05′	13′–0″	12′–11¾″	– ¼″
18′..........	100.37	100.38	+.01′	18′–0″	18′– 0″	....
23′..........	100.35	100.36	+.01′	23′–0″	23′– 0″	....
SW						
8′........	100.36	100.50	+.14′	8′–0″	8′– 1¾″	+1¾″
13′..........	100.41	100.45	+.04′	13′–0″	13′– 0″	....
18′..........	100.42	100.45	+.13′	18′–0″	18′– 0″	....
23′..........	100.48	100.48	+.0	23′–0″	23′– 0″	....
S						
8′...........	100.44	100.54	+.10′	8′–0″	8′– 2″	+2″
13′..........	100.44	100.47	+.03′	13′–0″	13′– 0″	....
18′..........	100.54	100.56	+.02′	18′–0″	18′– 0″	....
23′..........	100.54	100.54	.0	23′–0″	23′– 0″	....
SE						
8′...........	100.46	100.56	+.10′	8′–0″	8′– 1¼″	+1¼″
13′..........	100.48	100.52	+.04′	13′–0″	13′– 0¼″	+ ¼″
18′..........	100.51	100.53	+.02′	18′–0″	18′– 0″	....
23′..........	100.55	100.55	.0	23′–0″	23′– 0″	....
E						
8′...........	100.43	100.53	+.10′	8′–0″	8′– 2″	+2″
13′..........	100.46	100.50	+.04′	13′–0″	12′–11¾″	– ¼″
18′..........	100.46	100.46	.0	18′–0″	18′– 0″	....
24′..........	100.55	100.55	.0	24′–0″	24′– 0″	....
NE						
8′...........	100.38	100.44	+.06′	8′–0″	8′– 2″	+2″
13′..........	100.38	100.41	+.03′	13′–0″	13′– 0″	....
18′..........	100.45	100.46	+.01′	18′–0″	18′– 0″	....
23′..........	100.52	100.52	.0	23′–0″	23′– 0″	....

MODEL IGLOO TEST NO. 7

	Original elevation	Remeasured elevation	Difference	Original distance	Remeasured distance	Difference
N						
8′	99.93	99.99	+0.06′	8′–0″	8′–0⅝″	+⅝″
13′	99.89	99.93	+.04′	13′–0″	13′–0″	....
18′	99.86	99.88	+.02′	18′–0″	18′–0″	....
23′	99.82	99.83	+.01′	23′–0″	23′–0″	....
NW						
8′	99.91	100.02	+.11′	8′–0″	8′–1¾″	+1¾″
13′	99.96	100.01	+.05′	13′–0″	13′–0″	....
18′	99.94	99.96	+.02′	18′–0″	18′–0″	....
23′	99.89	99.90	+.01′	23′–0″	23′–0″	....
W						
8′	99.97	100.29	+.32′	8′–0″	8′–2″	+2″
13′	99.97	100.04	+.07′	13′–0″	13′–0″	....
18′	99.98	100.01	+.03′	18′–0″	18′–0″	....
23′	100.03	100.05	+.02′	23′–0″	23′–0″	....
SW						
8′	99.99	100.22	+.23′	8′–0″	8′–1½″	+1½″
13′	99.99	100.05	+.06′	13′–0″	13′–0½″	+½″
18′	100.00	100.03	+.03′	18′–0″	18′–0″	....
23′	100.00	100.02	+.02′	23′–0″	23′–0″	....
S						
8′	99.99	100.07	+.08′	8′–0″	8′–0⅝″	+⅝″
13′	99.97	100.03	+.06′	13′–0″	13′–0″	....
18′	99.98	100.02	+.04′	18′–0″	18′–0″	....
23′	99.97	100.00	+.03′	23′–0″	23′–0″	....
SE						
8′	99.95	100.24	+.29′	8′–0″	8′–1¾″	+1¾″
13′	99.94	100.02	+.08′	13′–0″	13′–0½″	+½″
18′	99.98	100.02	+.04′	18′–0″	18′–0″	....
23′	99.92	99.96	+.04′	23′–0″	23′–0″	....
E						
8′	99.90	100.24	+.34′	8′–0″	8′–3½″	+3½″
13′	99.95	100.00	+.05′	13′–0″	13′–0¾″	+¾″
18′	99.98	99.99	+.01′	18′–0″	18′–0″	....
24′	99.90	99.90	+.0	24′–0″	24′–0″	....
NE						
8′	00.86	99.94	+.08′	8′–0″	8′–1½″	+1½″
13′	99.87	99.91	+.04′	13′–0″	13′–0″	....
18′	99.85	99.89	+.04′	18′–0″	18′–0″	....
23′	99.86	99.87	+.01′	23′–0″	23′–0″	....

TARGET IGLOO MOVEMENT NOTES

MODEL IGLOO TEST NO. 1-A

	Original elevation	Remeasured elevation	Difference
Finish floor	99.95	99.99	+0.04′
Top headwall north end	101.35	101.40	+.05′
Top barrel center igloo	101.30	101.34	+.04′
Top headwall south end	101.45	101.47	+.02′

Recheck on alinement showed north end moved 0¼ inch west; south end moved 0⅜ inch west. (Note this is a movement toward point of blast.) North headwall moved 0⅛ inch north; south end showed no movement.

Tests 1 and 2—No readings taken.

MODEL IGLOO TEST NO. 3

	Original elevation	Remeasured elevation	Difference
Finish floor	100.45	100.47	+0.02′
Top north headwall	101.84	101.86	+.02′
Top south headwall	101.83	101.85	+.02′

Recheck on alinement showed—north end igloo moved 0¼ inch east—south end, 0⅛ inch east—no movements north or south.

MODEL IGLOO TEST NO. 4

	Original elevation	Remeasured elevation	Difference
Finish floor	100.36	100.38	+0.02′
Top north headwall	101.76	Blown off	0
Top south headwall	101.77	101.86	+.09′

Recheck on alinement showed south end moved 0⅜ inch west—north end moved 1⅛ inch west. No movement north or south.

MODEL IGLOO TEST NO. 5

	Original elevation	Remeasured elevation	Difference
Finish floor	100.74	100.71	−0.03′
Top north headwall	102.13	Broken off	0
Top south headwall	102.17	102.23	+.06′

Recheck on alinement showed south end moved 1¾ inches east, north end moved 1 inch east. (Note this is a movement toward point of blast.) No movement north or south.

MODEL IGLOO TEST NO. 6

	Original elevation	Remeasured elevation	Difference
Finish floor	100.48	100.48	0
Top north headwall	101.88	101.88	0
Top south headwall	101.89	101.89	0

Recheck on alinement showed no movement in any direction

MODEL IGLOO TEST NO. 7

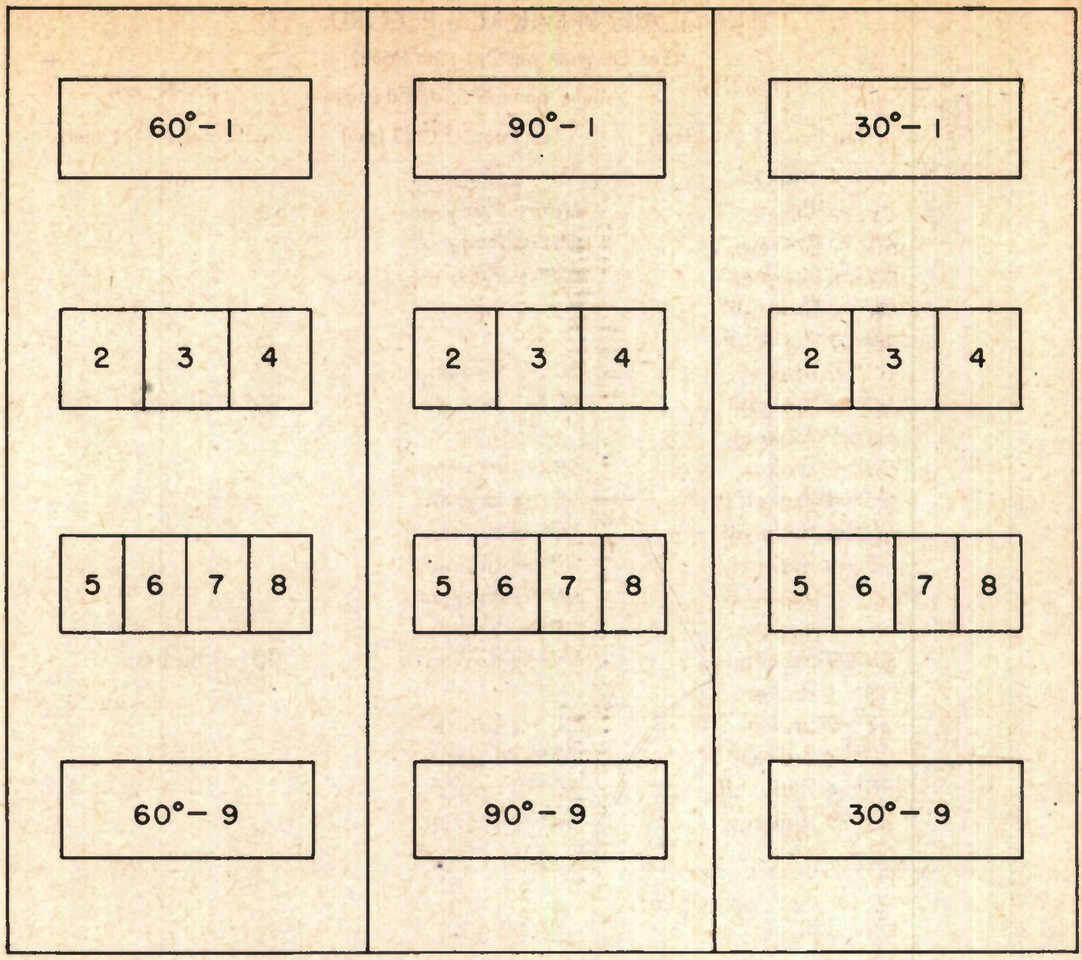
	Original elevation	Remeasured elevation	Difference
Finish floor	99.86	99.86	0
Top north headwall	101.25	101.25	0
Top south headwall	101.27	101.27	0

Recheck on alinement showed no movement in any direction.

GLASS BREAKAGE RECORD

(See Diagram on Opposite Page)

Test No.	Angle, pane No., and damage		
	Test Panel 1 (215 feet)	**Test Panel 2 (287 feet)**	**Test Panel 3 (431 feet)**
1		60°–1 Putty off	None.
	60°–9 Broken	60°–9 Putty off.	
	90°–1 Putty off	90°–1 Putty off.	
	90°–9 Broken	90°–9 Putty off.	
	30°–9 Putty off.		
2	60°–1 Putty off.		
	60°–9 Putty off	60°–9 Putty off.	
	90°–1 Broken	90°–1 Putty off.	
	90°–9 Putty off	90°–9 Broken	90°–9 Putty loose.
	30°–9 Putty off	30°–9 Putty off.	
3	60°–9 Putty off	60°–9 Putty off	None.
	90°–9 Broken.		
	30°–9 Putty off	30°–9 Putty off.	
Test No.	**1 (270 feet)**	**2 (360 feet)**	**3 (541 feet)**
4	60°–1 Putty off		None.
	60°–9 Broken.		
	90°–1 Out, not broken.		
	90°–9 Putty off	90°–9 Putty off.	
	30°–1 Putty off.		
	30°–9 Putty off.		
5	60°–1 Putty loose	None	None.
	90°–9 Broken.		
Test No.	**0 (144 feet)**	**1 (215 feet)**	**2 (287 feet)**
6	60°–1 Broken	60°–1 Putty off.	
	60°–2 Broken.		
	60°–3 Broken.		
	60°–4 Broken.		
	60°–9 Broken	60°–9 Broken.	
	90°–1 Broken	90°–1 Broken	90°–1 Putty loose.
	90°–2 Broken	90°–2 Loose.	
	90°–3 Broken	90°–3 Broken.	
	90°–4 Broken	90°–4 Loose.	
	90°–5 Putty off.		
	90°–6 Putty off	90°–6 Putty off.	
	90°–7 Putty off	90°–7 Putty off.	
	90°–8 Putty off.		



Angle 60° Angle 90° Angle 30°

NOTE –

Angles above are measured between plane of glass & line from explosion.

GLASS BREAKAGE RECORD

Model Tests 1 To 7

GLASS BREAKAGE RECORD (continued)

Test No.	0 (144 feet)	1 (215 feet)	2 (287 feet)
6	90°–9 Broken..........	90°–9 Broken.........	90°–9 Broken.
	30°–1 Broken..........	30°–1 Putty off.	
	30°–2 Broken.		
	30°–3 Broken..........	30°–3 Putty off.	
	....	30°–4 Putty off.	
	30°–6 Putty off.		
	30°–7 Putty off.		
	30°–9 Broken..........	30°–9 Putty off........	30°–9 Putty off.

Test No.	0 (144 feet)	1 (215 feet)	2 (287 feet)
7	60°–1 Broken	60°–1 Broken.	
	60°–2 Broken	60°–2 Putty off.	
	60°–3 Broken	60°–3 Putty off.	
	60°–4 Broken	60°–4 Putty off.	
	60°–5 Putty off.		
	60°–6 Putty off.		
	60°–9 Broken	60°–9 Broken.	
	90°–1 Broken	90°–1 Broken	90°–1 Broken.
	90°–2 Broken.		
	90°–3 Broken	90°–3 Broken.	
	90°–4 Broken	90°–4 Broken.	
	90°–5 Putty off	90°–5 Broken.	
	90°–6 Broken	90°–6 Broken.	
		90°–7 Broken.	
		90°–8 Broken.	
	90°–9 Broken	90°–9 Broken	90°–9 Broken.
	30°–1 Broken.		
	30°–2 Broken	30°–2 Loose.	
	30°–3 Broken	30°–3 Loose.	
	30°–4 Putty off	30°–4 Loose.	
	30°–9 Broken	30°–9 Broken.	

APPENDIX B. CALIBRATION OF BLAST METERS AND GAGES

1. Plywood Box Foil Meters.

This calibration was done at the Naval Proving Ground, Arco, Idaho.

Twelve meters were loaded with 0.0007 inch 250 aluminum foil and set up along a radius at distances ranging from 30 to 110 feet from a standard 100-pound charge of TNT.† The meters were mounted on wood stands about 5 feet above the ground and were oriented "side-on" to the blast, that is, the place of the orifice plate (and the foil) was parallel to a line from the charge to the meter. The charge was in the form of a right circular cylinder, 12 inches in diameter and 16 inches high, and was set with its long axis vertical on a wood stand of such height that the center of the charge was 5 feet above ground. Five shots were made with this arrangement. Peak pressures existing at each of the distances at which meters were placed were determined from the pressure-distance relation for the 100-pound charges of TNT given in reference 8, part VII. As the closest meter in this calibration was 30 feet from the charge, it was necessary to extrapolate from 50 feet, which is the lowest distance for which a pressure is given in reference 8. It was assumed that the relation $P=10{,}060/D^{1.79}$ (in which P is peak pressure, lb./in.^{2} gage, and D distance from charge in feet), which closely fits the data of reference 8, held true down to a distance of 30 feet.‡ In the calibration shots, readings were taken by recording the smallest hole in which the diaphragm was ruptured in each meter. These readings are recorded on page 129.

† The diameters of the orifices in the meters, which had been stated to be 3½, 2½, 1⅞, 1 7/16, 1⅛, 15/16, 13/16, 11/16, ⅝, 9/16, ½ and 7/16 inches, were measured and found to be 3.52, 2.58, 1.97, 1.49, 1.15, 0.92, 0.84, 0.71, 0.63, 0.61, 0.51, and 0.46 inches.

‡ It was further assumed that the effect of the elevation above sea level (4,850 feet) of the site on the peak pressures (gage) resulting from detonation of the standard charge was negligible.

Distance from charge (feet)	Peak pressure (lb./in.²)	Diameter of smallest diaphragm ruptured (inches)					
		Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Arithmetic mean
30	22.8	0.46	0.46	0.46	0.46	0.51	0.47
34	18.0	.51	.71	.61	.46	.46	.55
38	14.9	.63	.63	.51	.51	.71	.60
43	11.9	.71	.92	.84	.71	.92	.82
48	9.76	.92	.92	1.15	1.15	1.15	1.06
54	7.89	1.49	1.97	1.49	1.97	1.49	1.68
61	6.32	1.97	1.97	1.97	2.58	1.97	2.09
69	5.06	1.97	2.58	2.58	2.58	2.58	2.46
78	4.08	2.58	3.52	3.52	3.52	3.52	3.33
88	3.27	3.52	3.52	3.52	3.52	3.52	3.52
99	2.64	3.52	(*)	2.58	(*)	3.52	3.92
110	2.19	3.52	(*)	3.52	3.52	(*)	4.11

*No rupture occurred. In calculating the arithmetic mean diameter, an assumption was made in these cases that a hole of next larger diameter was present and was ruptured. Next larger diameter was assumed to be 5 inches.

The arithmetic mean diameter corresponding to each pressure is considered to be that diameter of diaphragm which, were it present, would be most frequently the smallest one ruptured by that pressure. Since these values of pressure vs. diameter when plotted on a logarithmic paper approximate a straight line, a relation of the form $p=ad^b$ (where p is peak blast pressure, lb./in.² gage, d is hole diameter in inches, and a and b are constants) was assumed to hold true. The constants were calculated by the method of least squares and were found to be: $a=10.66$, $b=-0.933$. From this equation, the pressures corresponding to the actual hole sizes in the meter were calculated to be:

Diameter (in.)	3.52	2.58	1.97	1.49	1.15	0.92
Pressure (lb./in.²)	3.3	4.4	5.6	7.25	9.4	11.5
Diameter, in	0.84	0.71	0.63	0.61	0.51	0.46
Pressure, lb./in.²	12.5	14.7	16.5	16.8	20.0	22.0

These pressures are considered to be those which must exist if the corresponding hole diameters are those most frequently the smallest ones ruptured. In measuring blast pressure at a point with a single meter, the smallest hole ruptured is regarded as the size most frequently the smallest ruptured, whence the most probable pressure is that given above for the corresponding size of hole. If a number of meters were placed at the same distance, an arithmetic mean smallest hole ruptured could be determined, from which a more probable pressure could be calculated by recourse to the formula $p=10.66d^{-0.933}$. By placing a number of meters on a radial line and plotting the diameters of the smallest holes ruptured versus distances on logarithmic paper, an average straight line may be drawn from which mean diameter may be picked off for each distance, whence pressure may be calculated from the formula. However, by plotting the pressures given above for each hole diameter directly against distance, an average straight line may be drawn which gives pressures at all distances very close to those calculated from the formula using the mean diameters, and a step is saved.

2. Ball Crusher Gages.

These gages were calibrated by computation according to the theory presented in reference 7, part VII, allowance being made for the fact that it deals with underwater explosions instead of explosions in air. The equation for the initial part of the pressure-time curve for a shock wave in water is assumed to be:

$$p=P_o e^{-\mu t} \tag{1}$$

where p=pressure lbs./in.^{2} gage at any time t.
P_o=peak or initial pressure, lb./in^2. gage.
e=2.71828.
μ=decay constant for pressure underwater, sec.$^{-1}$.
t=time in seconds after arrival of shock front.

The equation of motion of the piston is

$$M\frac{d^2x}{dt^2}+kx=AP_o e^{-\mu t} \tag{2}$$

where M=mass of moving parts, assumed to be that of piston plus ⅓ of copper ball; for ⁵⁄₃₂-inch ball in NOL gage, 0.958×10^{-3} slugs; in Arco gage, 6.89×10^{-3} slugs.
x=movement of piston = deformation of ball at any time t; inches.
A=area of piston, in^2, 0.197 sq. in. for NOL gage; 1.00 sq. in. for Arco gage.
k=restoring force constant of ⁵⁄₃₂-inch ball from tarage table (on straight-line portion of curve), increased by 20 percent to allow for greater resistance of copper at high rates of strain; 143,200 lbs./ft.

The solution of (2) is

$$x=\frac{AP_o}{M\mu^2+k}\left(\frac{\mu}{\omega}\sin\omega t-\cos\omega t\, e^{-\mu t}\right) \tag{3}$$

where $\omega=\sqrt{k/M}$

Since the elastic limit of the copper is exceeded it is assumed that the ball retains its deformation at the maximum value of x, which occurs when the first derivative of (3) is zero, or

$$\frac{dx}{dt}=\frac{AP_o}{M\mu^2+k}(\mu\cos\omega t+\sin\omega t-\mu e^{-\mu t})=0 \tag{4}$$

or when

$$\cos\omega t+\frac{\omega}{\mu}\sin\omega t=e^{-\mu t} \tag{5}$$

In order to use the water form of the equations for explosions in air, some assumptions are made. A value of μ is sought which will give equation (1) the same initial slope as the equation for pressure in the air shock wave, the latter being

$$p=P_o\left(1-\frac{t}{\lambda}\right)e^{-\frac{t}{\theta}} \tag{6}$$

(in which λ and θ are constants with units of seconds) (λ is the time at which the pressure reaches zero).
and its initial slope being

$$(t=0)\frac{dp}{dt}=-P_o\left(\frac{1}{\lambda}+\frac{1}{\theta}\right). \tag{7}$$

From experience it has been shown that for air blast waves of the order being handled in these tests, the relation $\theta=1.42\ \lambda$ holds approximately true, whence .

$$(t=0)\frac{dp}{dt}=-1.705\frac{P_o}{\lambda}. \tag{8}$$

The initial slope of the water shock wave is

$$(t=0)\frac{dp}{dt}=-\mu P_o. \tag{9}$$

Equating (8) and (9),

$$\mu=\frac{1.705}{\lambda}. \tag{10}$$

In using $\frac{1.705}{\lambda}$ for μ in determining the maximum deformation of the copper ball, a water blast wave of a form close to that of the air blast wave (during the first part of the pressure-time curve when the deformation is taking place) is assumed to exist.

A further assumption is made that the value of λ in seconds is determined by the relation $\lambda=0.0002d$, where d is distance in feet from charge, independently of the charge weight. This is also an approximation based on experience.

Values of μ are determined from (10) for the various distances at which the gages were placed from the charges in these tests, that is, from 7 to

14 feet. These μ's are substituted together with ω in equation (5) which is solved for t, which is in turn substituted in equation (3) in which the maximum deformations Δ are then expressed as various constants K times P_0, or

$$\Delta = K P_0.$$

whence

$$P_0 = \frac{\Delta}{K}. \tag{11}$$

These constants are tabulated below against the distances for which they were calculated:

d, feet	7	10	12	15	16	18
$\frac{K}{\text{in.} \times 10^6/\text{lb./in.}^2}$	28.8	29.8	30.2	30.6	30.7	30.9

Constants were also calculated for the large explosions of 250,000 and 500,000 pounds TNT wherein gages were placed at distances of from 100 to 160 feet from the center of the charge. These values are:

d, feet	100	110	120	130	140	150	160
$\frac{K,}{\text{in.} \times 10^6/\text{lb./in.}^2}$	32.7	32.8	32.8	32.8	32.8	32.8	32.9

The latter values are rapidly nearing the limit of 33.0 which is approached when d is very large, making λ very large and μ nearly zero.

In a similar manner, the constants for the Arco modification of the NOL gage were determined to be as follows:

d, feet	10	12	14	16	100	120	140	160
$\frac{K,}{\text{in.} \times 10^6/\text{lb./in.}^2}$	129	134	138	140.6	163	163.7	164.2	164.4

The advantage of the "Arco" gage having the 1 sq. in. piston is that greater ball deformations are obtained and the range is greatly extended toward the lower pressures, which is found desirable in working with explosions in air. However, the greater piston mass makes the gage slower acting and more subject to erratic behavior due to ground shock or other causes, and errors in the various assumptions made in these calculations have greater relative effect in throwing the values of K off.

The gage constants determined by the foregoing method are approximations which are considered closer to the true values than either the static constants from the tarage table or the theoretical values obtained from assuming the blast wave has a step shape with no pressure decay (which would be the case if μ were zero), the latter constant being twice the former.

U. S. GOVERNMENT PRINTING OFFICE O—1947